# Structural and Civionic
# Engineering
## (Concepts and Applications)



Delmer Amaya

Melia Meek

# Table of Contents

# Chapter- 1

# Structural Engineering



Burj Khalifa, in Dubai, the world's tallest building, shown under construction in 2007 (since completed)

**Structural engineering** is a field of engineering dealing with the analysis and design of structures that support or resist loads. Structural engineering is usually considered a specialty within civil engineering, but it can also be studied in its own right. Structural

engineers are most commonly involved in the design of buildings and large nonbuilding structures but they can also be involved in the design of machinery, medical equipment, vehicles or any item where structural integrity affects the item's function or safety. Structural engineers must ensure their designs satisfy given design criteria, predicated on safety (e.g. structures must not collapse without due warning) or serviceability and performance (e.g. building sway must not cause discomfort to the occupants). Buildings are made to endure massive loads as well as changing climate and natural disasters.

Structural engineering theory is based upon physical laws and empirical knowledge of the structural performance of different landscapes and materials. Structural engineering design utilises a relatively small number of basic structural elements to build up structural systems that can be very complex. Structural engineers are responsible for making creative and efficient use of funds, structural elements and materials to achieve these goals.

## Structural engineer

Structural engineers are responsible for engineering design and analysis. Entry-level structural engineers may design the individual structural elements of a structure, for example the beams, columns, and floors of a building. More experienced engineers would be responsible for the structural design and integrity of an entire system, such as a building.

Structural engineers often specialize in particular fields, such as bridge engineering, building engineering, pipeline engineering, industrial structures, or special mechanical structures such as vehicles or aircraft.

Structural engineering has existed since humans first started to construct their own structures. It became a more defined and formalised profession with the emergence of the architecture profession as distinct from the engineering profession during the industrial revolution in the late 19th Century. Until then, the architect and the structural engineer were usually one and the same - the master builder. Only with the development of specialised knowledge of structural theories that emerged during the 19th and early 20th centuries did the professional structural engineer come into existence.

The role of a structural engineer today involves a significant understanding of both static and dynamic loading, and the structures that are available to resist them. The complexity of modern structures often requires a great deal of creativity from the engineer in order to ensure the structures support and resist the loads they are subjected to. A structural engineer will typically have a four or five year undergraduate degree, followed by a minimum of three years of professional practice before being considered fully qualified.

Structural engineers are licensed or accredited by different learned societies and regulatory bodies around the world (for example, the Institution of Structural Engineers in the UK). Depending on the degree course they have studied and/or the jurisdiction they

are seeking licensure in, they may be accredited (or licensed) as just structural engineers, or as civil engineers, or as both civil and structural engineers.

## *History of structural engineering*



Pont du Gard, France, a Roman era aqueduct circa 19 BC

Structural engineering dates back to 2700 BC when the step pyramid for Pharaoh Djoser was built by Imhotep, the first engineer in history known by name. Pyramids were the most common major structures built by ancient civilizations because the structural form of a pyramid is inherently stable and can be almost infinitely scaled (as opposed to most other structural forms, which cannot be linearly increased in size in proportion to increased loads).

Throughout ancient and medieval history most architectural design and construction was carried out by artisans, such as stone masons and carpenters, rising to the role of master builder. No theory of structures existed, and understanding of how structures stood up was extremely limited, and based almost entirely on empirical evidence of 'what had worked before'. Knowledge was retained by guilds and seldom supplanted by advances. Structures were repetitive, and increases in scale were incremental.

No record exists of the first calculations of the strength of structural members or the behaviour of structural material, but the profession of structural engineer only really took

shape with the industrial revolution and the re-invention of concrete. The physical sciences underlying structural engineering began to be understood in the Renaissance and have been developing ever since.

## Structural failure

The history of structural engineering contains many collapses and failures. Sometimes this is due to obvious negligence, as in the case of the Pétionville school collapse, in which Rev. Fortin Augustin said that *"he constructed the building all by himself, saying he didn't need an engineer as he had good knowledge of construction"* following a partial collapse of the three-story schoolhouse that sent neighbors fleeing. The final collapse killed at least 362 people, mostly children.

In other cases structural failures require careful study, and the results of these inquiries have resulted in improved practices and greater understanding of the science of structural engineering. Some such studies are the result of Forensic engineering investigations where the original engineer seems to have done everything in accordance with the state of the profession and acceptable practice yet a failure still eventuated. A famous case of structural knowledge and practice being advanced in this manner can be found in a series of failures involving Box girders which collapsed in Australia during the 1970s.

## *Specializations*

### Building structures



Sydney Opera House, designed by Ove Arup & Partners, with the architect Jørn Utzon

Millennium Dome in London, UK, by Buro Happold and Richard Rogers

Structural building engineering includes all structural engineering related to the design of buildings. It is the branch of structural engineering that is close to architecture.

Structural building engineering is primarily driven by the creative manipulation of materials and forms and the underlying mathematical and scientific ideas to achieve an end which fulfills its functional requirements and is structurally safe when subjected to all the loads it could reasonably be expected to experience. This is subtly different from architectural design, which is driven by the creative manipulation of materials and forms, mass, space, volume, texture and light to achieve an end which is aesthetic, functional and often artistic.

The architect is usually the lead designer on buildings, with a structural engineer employed as a sub-consultant. The degree to which each discipline actually leads the design depends heavily on the type of structure. Many structures are structurally simple and led by architecture, such as multi-storey office buildings and housing, while other structures, such as tensile structures, shells and gridshells are heavily dependent on their form for their strength, and the engineer may have a more significant influence on the form, and hence much of the aesthetic, than the architect.

The structural design for a building must ensure that the building is able to stand up safely, able to function without excessive deflections or movements which may cause fatigue of structural elements, cracking or failure of fixtures, fittings or partitions, or discomfort for occupants. It must account for movements and forces due to temperature, creep, cracking and imposed loads. It must also ensure that the design is practically buildable within acceptable manufacturing tolerances of the materials. It must allow the architecture to work, and the building services to fit within the building and function (air conditioning, ventilation, smoke extract, electrics, lighting etc.). The structural design of a modern building can be extremely complex, and often requires a large team to complete.

Structural engineering specialties for buildings include:

- Earthquake engineering
- Façade engineering
- Fire engineering
- Roof engineering
- Tower engineering
- Wind engineering

## Earthquake engineering structures

**Earthquake engineering structures** are those engineered to withstand various types of hazardous earthquake exposures at the sites of their particular location.



Earthquake-proof and massive pyramid El Castillo, Chichen Itza

Earthquake engineering is treating its subject structures like defensive fortifications in military engineering but for the warfare on earthquakes. Both earthquake and military general design principles are similar: be ready to slow down or mitigate the advance of a possible attacker.

The main objectives of **earthquake engineering** are:
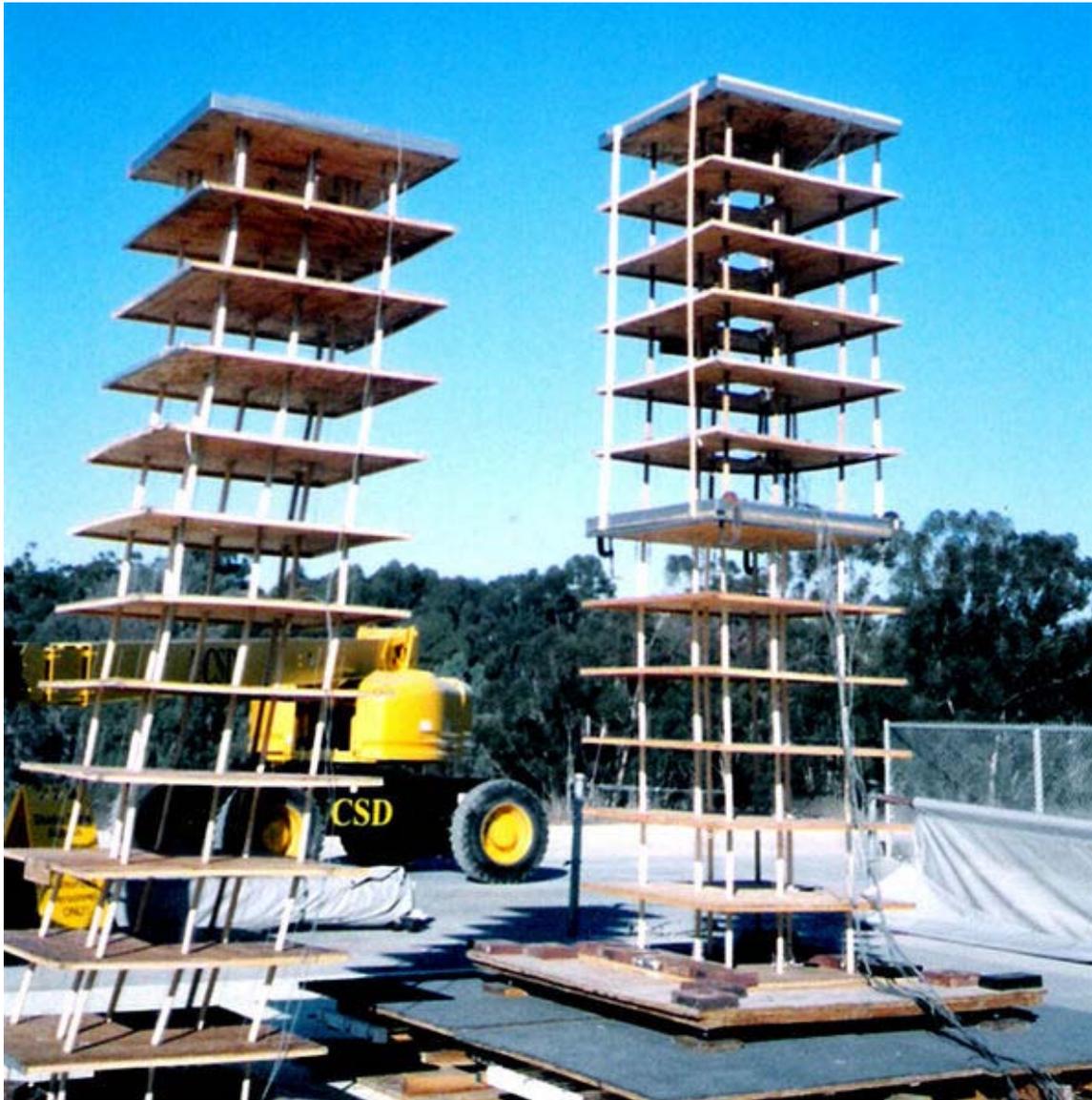


Snapshot from shake-table testing base-isolated (right) and regular (left) building model

- Understand interaction of structures with the shaky ground.

- Foresee the consequences of possible earthquakes.

- Design and construct the structures to perform while being exposed to an earthquake.

**Earthquake engineering** or **earthquake-proof structure** does not, necessarily, means *extremely strong* and *expensive* one like El Castillo pyramid at Chichen Itza shown

above. In fact, many structures considered *strong* may in fact be actually *stiff,* which may result in poor seismic performance.

Now, the most *powerful* and *budgetary* tool of the earthquake engineering is base isolation which pertains to the passive structural vibration control technologies.

## Civil engineering structures

Civil structural engineering includes all structural engineering related to the built environment. It includes:

- Bridges
- Dams
- Earthworks
- Foundations
- Offshore structures
- Pipelines

- Power stations
- Railways
- Retaining structures and walls
- Roads
- Tunnels
- Waterways
- Water and wastewater infrastructure

The structural engineer is the lead designer on these structures, and often the sole designer. In the design of structures such as these, structural safety is of paramount importance (in the UK, designs for dams, nuclear power stations and bridges must be signed off by a chartered engineer).

Civil engineering structures are often subjected to very extreme forces, such as large variations in temperature, dynamic loads such as waves or traffic, or high pressures from water or compressed gases. They are also often constructed in corrosive environments, such as at sea, in industrial facilities or below ground.

## Mechanical structures



An Airbus A380, the world's largest passenger airliner

Principals of structural engineering are applied to variety of mechanical (moveable) structures. The design of static structures assumes they always have the same geometry (in fact, so-called static structures can move significantly, and structural engineering design must take this into account where necessary), but the design of moveable or moving structures must account for fatigue, variation in the method in which load is resisted and significant deflections of structures.

The forces which parts of a machine are subjected to can vary significantly, and can do so at a great rate. The forces which a boat or aircraft are subjected to vary enormously and will do so thousands of times over the structure's lifetime. The structural design must ensure that such structures are able to endure such loading for their entire design life without failing.

These works can require mechanical structural engineering:

- Airframes and fuselages
- Boilers and pressure vessels
- Coachworks and carriages
- Cranes
- Elevators
- Escalators
- Marine vessels and hulls

## *Structural elements*
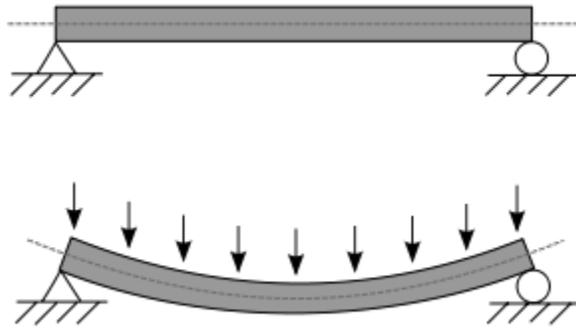




A statically determinate simply supported beam, bending under an evenly distributed load.

Any structure is essentially made up of only a small number of different types of elements:

- Columns
- Beams
- Plates
- Arches
- Shells
- Catenaries

Many of these elements can be classified according to form (straight, plane / curve) and dimensionality (one-dimensional / two-dimensional):

|  | One-dimensional | | Two-dimensional | |
|---|---|---|---|---|
|  | straight | curve | plane | curve |
| (predominantly) bending | beam | continuous arch | plate, concrete slab | lamina, dome |
| (predominant) tensile stress | rope | Catenary | shell | |
| (predominant) compression | pier, column | | Load-bearing wall | |

## Columns

Columns are elements that carry only axial force - either tension or compression - or both axial force and bending (which is technically called a beam-column but practically, just a column). The design of a column must check the axial capacity of the element, and the buckling capacity.

The buckling capacity is the capacity of the element to withstand the propensity to buckle. Its capacity depends upon its geometry, material, and the effective length of the

column, which depends upon the restraint conditions at the top and bottom of the column. The effective length is $K * l$ where $l$ is the real length of the column.

The capacity of a column to carry axial load depends on the degree of bending it is subjected to, and vice versa. This is represented on an interaction chart and is a complex non-linear relationship.

## Beams

A beam may be defined as an element in which one dimemsion is much greater than the other two and the applied loads are usually normal to the main axis of the element. Beams and columns are called line elements and are often represented by simple lines in structural modeling.

- cantilevered (supported at one end only with a fixed connection)
- simply supported (supported vertically at each end; horizontally on only one to withstand friction, and able to rotate at the supports)
- continuous (supported by three or more supports)
- a combination of the above (ex. supported at one end and in the middle)

Beams are elements which carry pure bending only. Bending causes one part of the section of a beam (divided along its length) to go into compression and the other part into tension. The compression part must be designed to resist buckling and crushing, while the tension part must be able to adequately resist the tension.
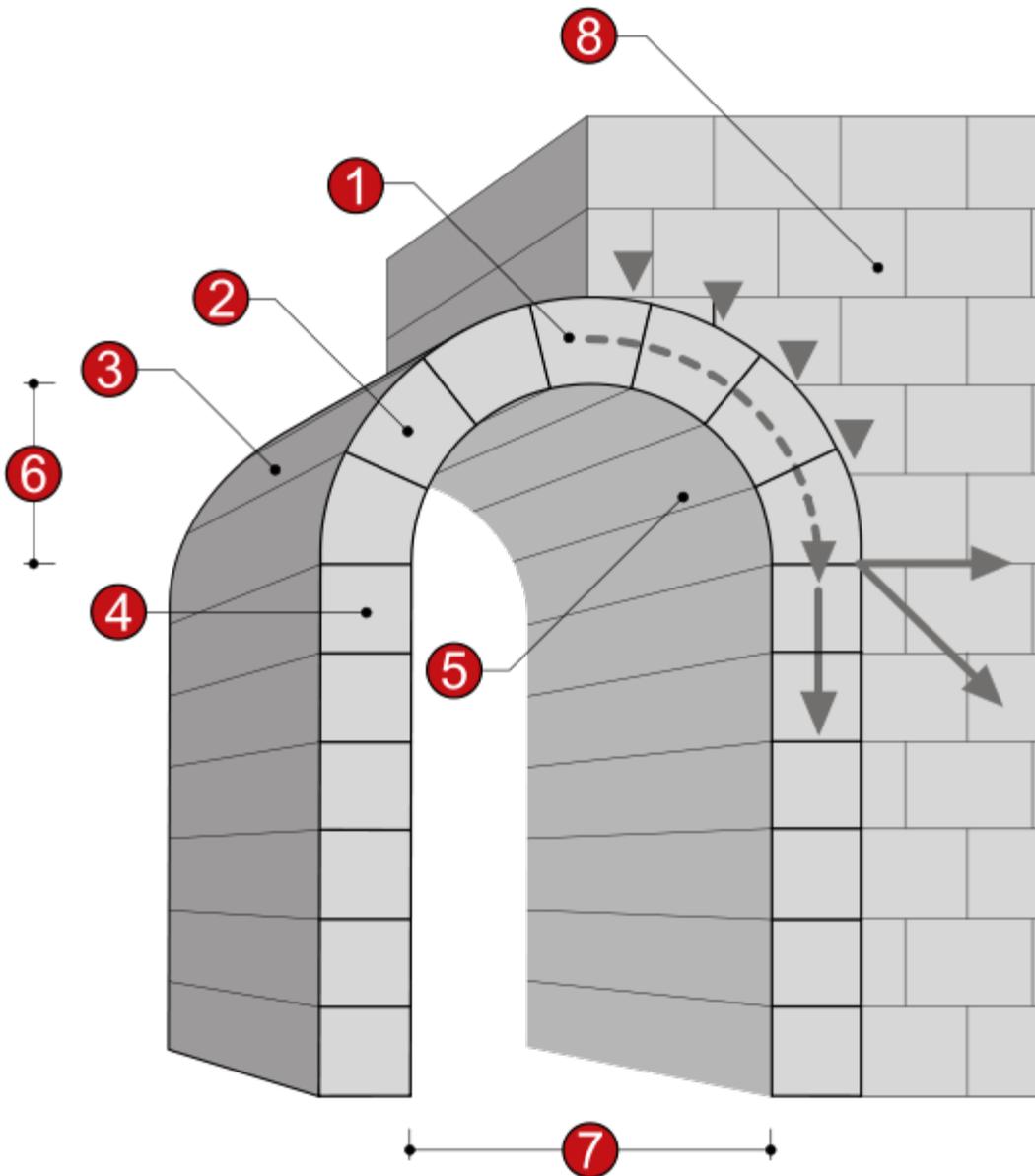
**Struts and ties**



*Little Belt*: a truss bridge in Denmark



The McDonnell Planetarium by Gyo Obata in St Louis, Missouri, USA, a concrete shell structure

A masonry arch
1. Keystone 2. Voussoir 3. Extrados 4. Impost 5. Intrados 6. Rise 7. Clear span
8. Abutment

A truss is a structure comprising two types of structural elements; compression members and tension members (i.e. struts and ties). Most trusses use gusset plates to connect intersecting elements. Gusset plates are relatively flexible and minimize bending moments at the connections, thus allowing the truss members to carry primarily tension or compression.

Trusses are usually utilised in span large distances, where it would be uneconomical to use solid beams.

## Plates

Plates carry bending in two directions. A concrete flat slab is an example of a plate. Plates are understood by using continuum mechanics, but due to the complexity involved they are most often designed using a codified empirical approach, or computer analysis.

They can also be designed with yield line theory, where an assumed collapse mechanism is analysed to give an upper bound on the collapse load. This is rarely used in practice.

## Shells

Shells derive their strength from their form, and carry forces in compression in two directions. A dome is an example of a shell. They can be designed by making a hanging-chain model, which will act as a catenary in pure tension, and inverting the form to achieve pure compression.

## Arches

Arches carry forces in compression in one direction only, which is why it is appropriate to build arches out of masonry. They are designed by ensuring that the line of thrust of the force remains within the depth of the arch.

## Catenaries

Catenaries derive their strength from their form, and carry transverse forces in pure tension by deflecting (just as a tightrope will sag when someone walks on it). They are almost always cable or fabric structures. A fabric structure acts as a catenary in two directions.
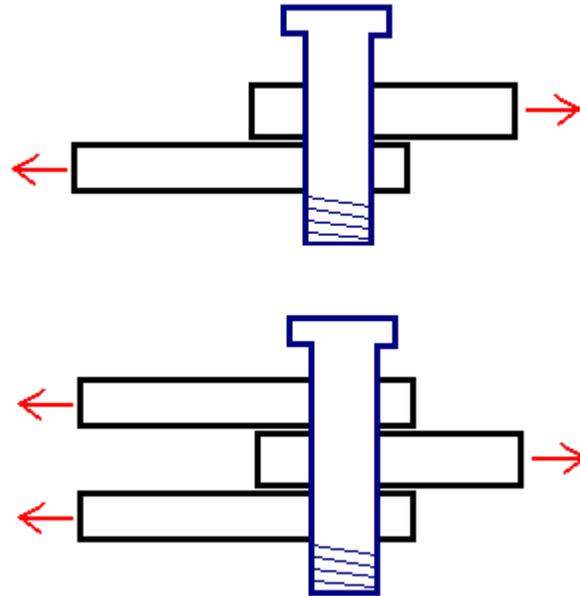
## *Structural engineering theory*



Figure of a bolt in shear stress. Top figure illustrates single shear, bottom figure illustrates double shear.

Structural engineering depends upon a detailed knowledge of loads, physics and materials to understand and predict how structures support and resist self-weight and imposed loads. To apply the knowledge successfully a structural engineer generally requires detailed knowledge of mathematics and relevant empirical and theoretical design codes. As well as, typically, some knowledge of the corrosion resistance of the materials and structures, especially when those structures are exposed to the external environment. Since the 1990s, specialist software has become available to aid in the design of structures, with the functionality to assist in both the drawing and designing of structures with maximum precision; examples include AutoCAD, StaadPro, Etab etc. Such software may also take into consideration environmental loads, such as from earthquakes and winds.

## *Materials*



The 630 foot (192 m) high, stainless-clad (type 304) Gateway Arch in Saint Louis, Missouri

Structural engineering depends on the knowledge of materials and their properties, in order to understand how different materials support and resist loads.

Common structural materials are:

- Iron:

    - Wrought iron
    - Cast iron
    - Steel
    - Stainless steel

- Concrete:

    - Reinforced concrete
    - Prestressed concrete

- Aluminium
- Composites
- Alloy
- Masonry
- Timber
- Other structural materials:

    - Adobe

- Bamboo
- Carbon fibre
- Fiber reinforced plastic
- Mudbrick

**Chapter- 2**
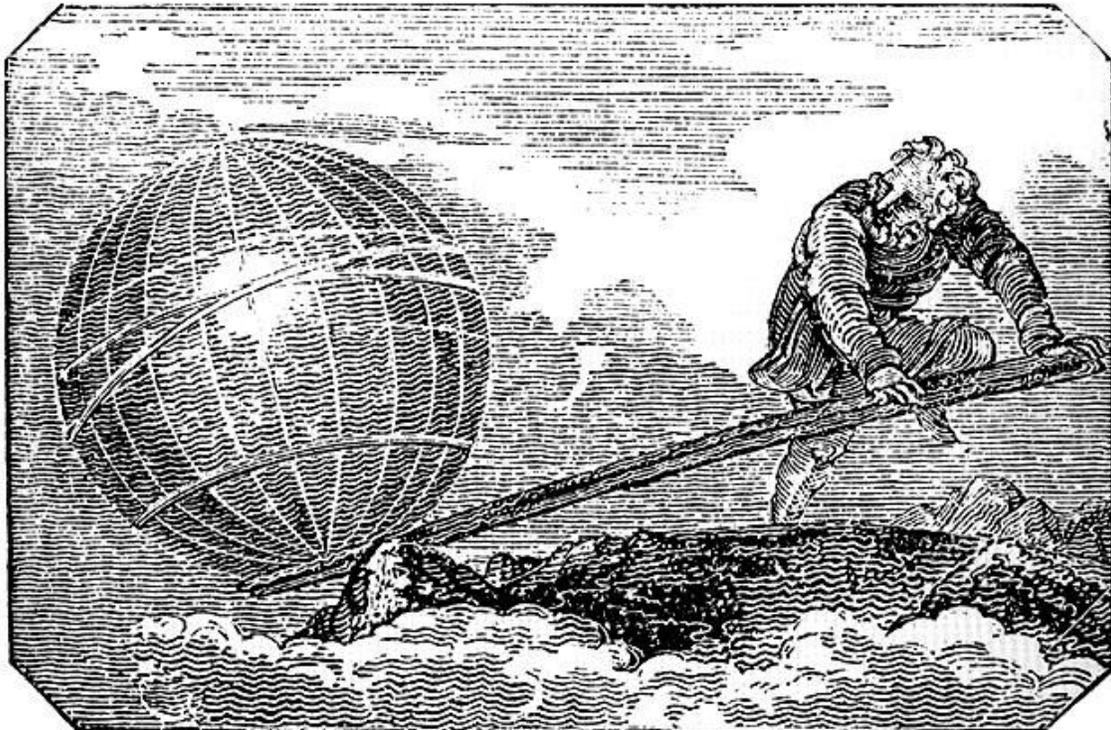
# History of Structural Engineering



Statuette of Imhotep, in the Louvre, Paris, France

The **history of structural engineering** dates back to at least 2700 BC when the step pyramid for Pharaoh Djoser was built by Imhotep, the first engineer in history known by name. Pyramids were the most common major structures built by ancient civilisations because it is a structural form which is inherently stable and can be almost infinitely scaled (as opposed to most other structural forms, which cannot be linearly increased in size in proportion to increased loads).

Throughout ancient and medieval history most architectural design and construction was carried out by artisans, such as stone masons and carpenters, rising to the role of master builder. No theory of structures existed and understanding of how structures stood up was extremely limited, and based almost entirely on empirical evidence of 'what had worked before'. Knowledge was retained by guilds and seldom supplanted by advances. Structures were repetitive, and increases in scale were incremental.

No record exists of the first calculations of the strength of structural members or the behaviour of structural material, but the profession of structural engineer only really took shape with the industrial revolution and the re-invention of concrete. The physical sciences underlying structural engineering began to be understood in the Renaissance and have been developing ever since.

## *Early structural engineering developments*



Archimedes is said to have remarked about the lever: "Give me a place to stand on, and I will move the Earth."

The recorded history of structural engineering starts with the ancient Egyptians. In the 27th century BC, Imhotep was the first structural engineer known by name and constructed the first known step pyramid in Egypt. In the 26th century BC, the Great Pyramid of Giza was constructed in Egypt. It remained the largest man-made structure for millennia and was considered an unsurpassed feat in architecture until the 19th century AD.

The understanding of the physical laws that underpin structural engineering dates back to the 3rd century BC, when Archimedes published his work *On the Equilibrium of Planes* in two volumes, in which he sets out the *Law of the Lever*, stating:

> " Equal weights at equal distances are in equilibrium, and equal weights at unequal distances are not in equilibrium but incline towards the weight "  which is at the greater distance.

Archimedes used the principles derived to calculate the areas and centers of gravity of various geometric figures including triangles, paraboloids, and hemispheres. Archimedes work on this and his work on calculus and geometry, together with Euclidean geometry, underpin much of the mathematics and understanding of structures in modern structural engineering.



Pont du Gard, France, a Roman era aqueduct circa 19 BC.

The ancient Romans made great bounds in structural engineering, pioneering large structures in masonry and concrete, many of which are still standing today. They include aqueducts, thermae, columns, lighthouses, defensive walls and harbours. Their methods are recorded by Vitruvius in his De Architectura written in 25 BC, a manual of civil and structural engineering with extensive sections on materials and machines used in construction. One reason for their success is their accurate surveying techniques based on the dioptra, groma and chorobates.

Centuries later, in the 15th and 16th centuries and despite lacking beam theory and calculus, Leonardo da Vinci produced many engineering designs based on scientific observations and rigour, including a design for a bridge to span the Bosporus. Though dismissed at the time, the design has since been judged to be both feasible and structurally valid

Galileo Galilei. Portrait in crayon by Leoni

The foundations of modern structural engineering were laid in the 17th century by Galileo Galilei, Robert Hooke and Isaac Newton with the publication of three great scientific works. In 1638 Galileo published *Dialogues Relating to Two New Sciences*, outlining the sciences of the strength of materials and the motion of objects (essentially

defining gravity as a force giving rise to a constant acceleration). It was the first establishment of a scientific approach to structural engineering, including the first attempts to develop a theory for beams. This is also regarded as the beginning of structural analysis, the mathematical representation and design of building structures.

This was followed in 1676 by Robert Hooke's first statement of Hooke's Law, providing a scientific understanding of elasticity of materials and their behaviour under load.

Eleven years later, in 1687, Sir Isaac Newton published *Philosophiae Naturalis Principia Mathematica*, setting out his Laws of Motion, providing for the first time an understanding of the fundamental laws governing structures.

Also in the 17th century, Sir Isaac Newton and Gottfried Leibniz both independently developed the Fundamental theorem of calculus, providing one of the most important mathematical tools in engineering.



Leonhard Euler portrait by Johann Georg Brucker

Further advances in the mathematics needed to allow structural engineers to apply the understanding of structures gained through the work of Galileo, Hooke and Newton during the 17th century came in the 18th century when Leonhard Euler pioneered much of the mathematics and many of the methods which allow structural engineers to model and analyse structures. Specifically, he developed the Euler-Bernoulli beam equation with Daniel Bernoulli (1700–1782) circa 1750 - the fundamental theory underlying most structural engineering design.

Daniel Bernoulli, with Johann (Jean) Bernoulli (1667–1748), is also credited with formulating the theory of virtual work, providing a tool using equilibrium of forces and compatibility of geometry to solve structural problems. In 1717 Jean Bernoulli wrote to Pierre Varignon explaining the principle of virtual work, while in 1726 Daniel Bernoulli wrote of the "composition of forces".

In 1757 Leonhard Euler went on to derive the Euler buckling formula, greatly advancing the ability of engineers to design compression elements.

## *Modern developments in structural engineering*



Bessemer converter, Kelham Island Museum, Sheffield, England (2002)

Belper North Mill



Eiffel Tower under construction in July 1888

The Forth Bridge

The Lattice shell structure of the Shukhov Tower in Moscow

Throughout the late 19th and early 20th centuries, materials science and structural analysis underwent development at a tremendous pace.

Though elasticity was understood in theory well before the 19th century, it was not until 1821 that Claude-Louis Navier formulated the general theory of elasticity in a mathematically usable form. In his *leçons* of 1826 he explored a great range of different structural theory, and was the first to highlight that the role of a structural engineer is not to understand the final, failed state of a structure, but to prevent that failure in the first place. In 1826 he also established the elastic modulus as a property of materials independent of the second moment of area, allowing engineers for the first time to both understand structural behaviour and structural materials.

Towards the end of the 19th century, in 1873, Carlo Alberto Castigliano presented his dissertation "Intorno ai sistemi elastici", which contains his theorem for computing displacement as partial derivative of the strain energy.

In 1824, Portland cement was patented by the engineer Joseph Aspdin as *"a superior cement resembling Portland Stone"*, British Patent no. 5022. Although different forms of cement already existed (Pozzolanic cement was used by the Romans as early as 100 B.C. and even earlier by the ancient Greek and Chinese civilizations) and were in common usage in Europe from the 1750s, the discovery made by Aspdin used commonly available, cheap materials, making concrete construction an economical possibility.

Developments in concrete continued with the construction in 1848 of a rowing boat built of ferrocement - the forerunner of modern reinforced concrete - by Joseph-Louis Lambot. He patented his system of mesh reinforcement and concrete in 1855, one year after W.B. Wilkinson also patented a similar system. This was followed in 1867 when a reinforced concrete planting tub was patented by Joseph Monier in Paris, using steel mesh reinforcement similar to that used by Lambot and Wilkinson. Monier took the idea forward, filing several patents for tubs, slabs and beams, leading eventually to the Monier system of reinforced structures, the first use of steel reinforcement bars located in areas of tension in the structure.

Steel construction was first made possible in the 1850s when Henry Bessemer developed the Bessemer process to produce steel. He gained patents for the process in 1855 and 1856 and successfully completed the conversion of cast iron into cast steel in 1858. Eventually mild steel would replace both wrought iron and cast iron as the preferred metal for construction.

During the late 19th century, great advancements were made in the use of cast iron, gradually replacing wrought iron as a material of choice. Ditherington Flax Mill in Shrewsbury, designed by Charles Bage, was the first building in the world with an interior iron frame. It was built in 1797. In 1792 William Strutt had attempted to build a fireproof mill at Belper in Derby (Belper West Mill), using cast iron columns and timber beams within the depths of brick arches that formed the floors. The exposed beam soffits were protected against fire by plaster. This mill at Belper was the world's first attempt to construct fireproof buildings, and is the first example of fire engineering. This was later improved upon with the construction of Belper North Mill, a collaboration between Strutt and Bage, which by using a full cast iron frame represented the world's first "fire proofed" building.

The Forth Bridge was built by Benjamin Baker, Sir John Fowler and William Arrol in 1889, using steel, after the original design for the bridge by Thomas Bouch was rejected following the collapse of his Tay Rail Bridge. The Forth Bridge was one of the first major uses of steel, and a landmark in bridge design. Also in 1889, the wrought-iron Eiffel Tower was built by Gustave Eiffel and Maurice Koechlin, demonstrating the potential of construction using iron, despite the fact that steel construction was already being used elsewhere.

During the late 19th century, Russian structural engineer Vladimir Shukhov developed analysis methods for tensile structures, thin-shell structures, lattice shell structures and new structural geometries such as hyperboloid structures. Pipeline transport was pioneered by Vladimir Shukhov and the Branobel company in the late 19th century.

Again taking reinforced concrete design forwards, from 1892 onwards François Hennebique's firm used his patented reinforced concrete system to build thousands of structures throughout Europe. Thaddeus Hyatt in the US and Wayss & Freitag in Germany also patented systems. The firm *AG für Monierbauten* constructed 200 reinforced concrete bridges in Germany between 1890 and 1897. The great pioneering uses of reinforced concrete however came during the first third of the 20th century, with Robert Maillart and others furthering of the understanding of its behaviour. Maillart noticed that many concrete bridge structures were significantly cracked, and as a result left the cracked areas out of his next bridge design - correctly believing that if the concrete was cracked, it was not contributing to the strength. This resulted in the revolutionary Salginatobel Bridge design. Wilhelm Ritter formulated the truss theory for the shear design of reinforced concrete beams in 1899, and Emil Mörsch improved this in 1902. He went on to demonstrate that treating concrete in compression as a linear-elastic material was a conservative approximation of its behaviour. Concrete design and analysis has been progressing ever since, with the development of analysis methods such as yield line theory, based on plastic analysis of concrete (as opposed to linear-elastic), and many different variations on the model for stress distributions in concrete in compression

Prestressed concrete, pioneered by Eugène Freyssinet with a patent in 1928, gave a novel approach in overcoming the weakness of concrete structures in tension. Freyssinet constructed an experimental prestressed arch in 1908 and later used the technology in a limited form in the Plougastel Bridge in France in 1930. He went on to build six prestressed concrete bridges across the Marne River, firmly establishing the technology.

Structural engineering theory was again advanced in 1930 when Professor Hardy Cross developed his Moment distribution method, allowing the real stresses of many complex structures to be approximated quickly and accurately.

In the mid 20th century John Fleetwood Baker went on to develop the plasticity theory of structures, providing a powerful tool for the safe design of steel structures.

High-rise construction, though possible from the late 19th century onwards, was greatly advanced during the second half of the 20th century. Fazlur Khan designed structural systems that remain fundamental to many modern high rise constructions and which he employed in his structural designs for the John Hancock Center in 1969 and Sears Tower in 1973. Khan's central innovation in skyscraper design and construction was the idea of the "tube" and "bundled tube" structural systems for tall buildings. He defined the framed tube structure as "a three dimensional space structure composed of three, four, or possibly more frames, braced frames, or shear walls, joined at or near their edges to form a vertical tube-like structural system capable of resisting lateral forces in any direction by cantilevering from the foundation." Closely spaced interconnected exterior columns form

the tube. Horizontal loads, for example wind, are supported by the structure as a whole. About half the exterior surface is available for windows. Framed tubes allow fewer interior columns, and so create more usable floor space. Where larger openings like garage doors are required, the tube frame must be interrupted, with transfer girders used to maintain structural integrity. The first building to apply the tube-frame construction was in the DeWitt-Chestnut Apartment Building which Khan designed in Chicago. This laid the foundations for the tube structures used in most later skyscraper constructions, including the construction of the World Trade Center.

Another innovation that Fazlur Khan developed was the concept of X-bracing, which reduced the lateral load on the building by transferring the load into the exterior columns. This allowed for a reduced need for interior columns thus creating more floor space, and can be seen in the John Hancock Center. The first sky lobby was also designed by Khan for the John Hancock Center in 1969. Later buildings with sky lobbies include the World Trade Center, Petronas Twin Towers and Taipei 101.

In 1987 Jörg Schlaich and Kurt Schafer published the culmination of almost ten years of work on the strut and tie method for concrete analysis - a tool to design structures with discontinuities such as corners and joints, providing another powerful tool for the analysis of complex concrete geometries.

In the late 20th and early 21st centuries the development of powerful computers has allowed finite element analysis to become a significant tool for structural analysis and design. The development of finite element programs has led to the ability to accurately predict the stresses in complex structures, and allowed great advances in structural engineering design and architecture. In the 1960s and 70s computational analysis was used in a significant way for the first time on the design of the Sydney Opera House roof. Many modern structures could not be understood and designed without the use of computational analysis.

Developments in the understanding of materials and structural behaviour in the latter part of the 20th century have been significant, with detailed understanding being developed of topics such as fracture mechanics, earthquake engineering, composite materials, temperature effects on materials, dynamics and vibration control, fatigue, creep and others. The depth and breadth of knowledge now available in structural engineering, and the increasing range of different structures and the increasing complexity of those structures has led to increasing specialisation of structural engineers.

# Chapter- 3

# Earthquake Engineering Structures



Earthquake-proof and massive pyramid El Castillo, Chichen Itza

**Earthquake engineering structures** are designed and constructed to withstand various types of hazardous earthquake exposures at the sites of their particular location.

Earthquake engineering is treating its subject structures like defensive fortifications in military engineering but for the warfare on earthquakes. Both earthquake and military general design principles are similar: be ready to slow down or mitigate the advance of a possible attacker.

According to building codes, earthquake engineering structures are meant to "withstand" the largest earthquake of a certain probability that is likely to occur at their location. This means the loss of life should be minimized by preventing collapse of the buildings.

Ancient architects believed that devastating earthquakes were a result of wrath of gods and therefore, could not be resisted by humans. Nowadays, the people's attitude has changed dramatically though the term "earthquake engineering structure" does not

necessarily mean it is an extremely strong or expensive one like the El Castillo pyramid at Chichen Itza.



Snapshot from shake-table testing base-isolated (right) and regular (left) building model

Currently, the most powerful and cost-effective tool of earthquake engineering is base isolation which makes use of passive structural vibration control technologies, used for example in the Cathedral of Our Lady of the Angels.

## *Trends and projects*

Some of the new state-of-the-art trends and/or projects in the field of earthquake engineering structures are presented below.

## Proofed low cost earthquake building material

A leading German composite construction company developed a proofed earthquake-safe supported core material RexWall - based on internal beam/frame constructions. The same principle allows construction of hurricane-safe houses.

## Earthquake shelter

One Japanese construction company has developed a six-foot cubical shelter, presented as an alternative to earthquake-proofing an entire building.

## Concurrent shake-table testing

**Concurrent shake-table testing** of two or more building models is a vivid, persuasive and effective way to validate earthquake engineering solutions experimentally.

Thus, two wooden houses built before adoption of the 1981 Japanese Building Code were moved to E-Defense for testing. The left house was reinforced to enhance its seismic resistance, while the other one was not. These two models were set on E-Defense platform and tested simultaneously.

**Combined vibration control solution**



Close-up of abutment of seismically retrofitted Municipal Services Building in Glendale, CA

Seismically retrofitted Municipal Services Building in Glendale, CA

Designed by architect Merrill W. Baird of Glendale, working in collaboration with A. C. Martin Architects of Los Angeles, the Municipal Services Building at 633 East Broadway, Glendale was completed in 1966. Prominently sited at the corner of East Broadway and Glendale Avenue, this civic building serves as a heraldic element of Glendale's civic center.

In October 2004 Architectural Resources Group (ARG) was contracted by Nabih Youssef & Associates, Structural Engineers, to provide services regarding a historic resource assessment of the building due to a proposed seismic retrofit.

In 2008, the Municipal Services Building of the City of Glendale, California was seismically retrofitted using an innovative combined vibration control solution: the existing elevated building foundation of the building was put on high damping rubber bearings.

**Steel plate shear walls system**



Coupled steel plate shear walls, Seattle

The Ritz-Carlton/JW Marriott hotel building engaging the advanced steel plate shear walls system, LA

A steel plate shear wall (SPSW) consists of steel infill plates bounded by a column-beam system. When such infill plates occupy each level within a framed bay of a structure, they constitute a SPSW system.

SPSW behavior is analogous to a vertical plate girder cantilevered from its base. Similar to plate girders, the SPSW system optimizes component performance by taking advantage of the post-buckling behavior of the steel infill panels.

The Ritz-Carlton/JW Marriott hotel building, a part of the LA Live development in Los Angeles, California, is the first building in Los Angeles that uses an advanced steel plate shear wall system to resist the lateral loads of strong earthquakes and winds.

**Kashiwazaki-Kariwa Nuclear Power Plant is partially upgraded**



Kashiwazaki-Kariwa Nuclear Power Plant: aerial view, Japan

The Kashiwazaki-Kariwa Nuclear Power Plant, the largest nuclear generating station in the world by net electrical power rating, happened to be near the epicenter of the strongest $M_w$ 6.6 July 2007 Chūetsu offshore earthquake. This initiated an extended shutdown for structural inspection which indicated that a greater earthquake-proofing was needed before operation could be resumed.

On May 9, 2009, one unit (Unit 7) was restarted, after the seismic upgrades. The test run had to continue for 50 days. The plant had been completely shut down for almost 22 months following the earthquake.

## Seismic Test of Seven-Story Building



Seven-story wooden structure prior to shake-table testing, Japan

A destructive earthquake struck a lone, wooden condominium in Japan. The experiment was webcast live on July 14, 2009 to yield insight on how to make wooden structures stronger and better able to withstand major earthquakes.

The Miki shake at the Hyogo Earthquake Engineering Research Center is the capstone experiment of the four-year NEESWood project, which receives its primary support from the U.S. National Science Foundation Network for Earthquake Engineering Simulation (NEES) Program.

"NEESWood aims to develop a new seismic design philosophy that will provide the necessary mechanisms to safely increase the height of wood-frame structures in active seismic zones of the United States, as well as mitigate earthquake damage to low-rise wood-frame structures," said Rosowsky, Department of Civil Engineering at Texas A&M University. This philosophy is based on the application of seismic damping systems for wooden buildings. The systems, which can be installed inside the walls of most wooden buildings, include strong metal frame, bracing and dampers filled with viscous fluid.

**Chapter- 4**

# Column (Structural Elements)
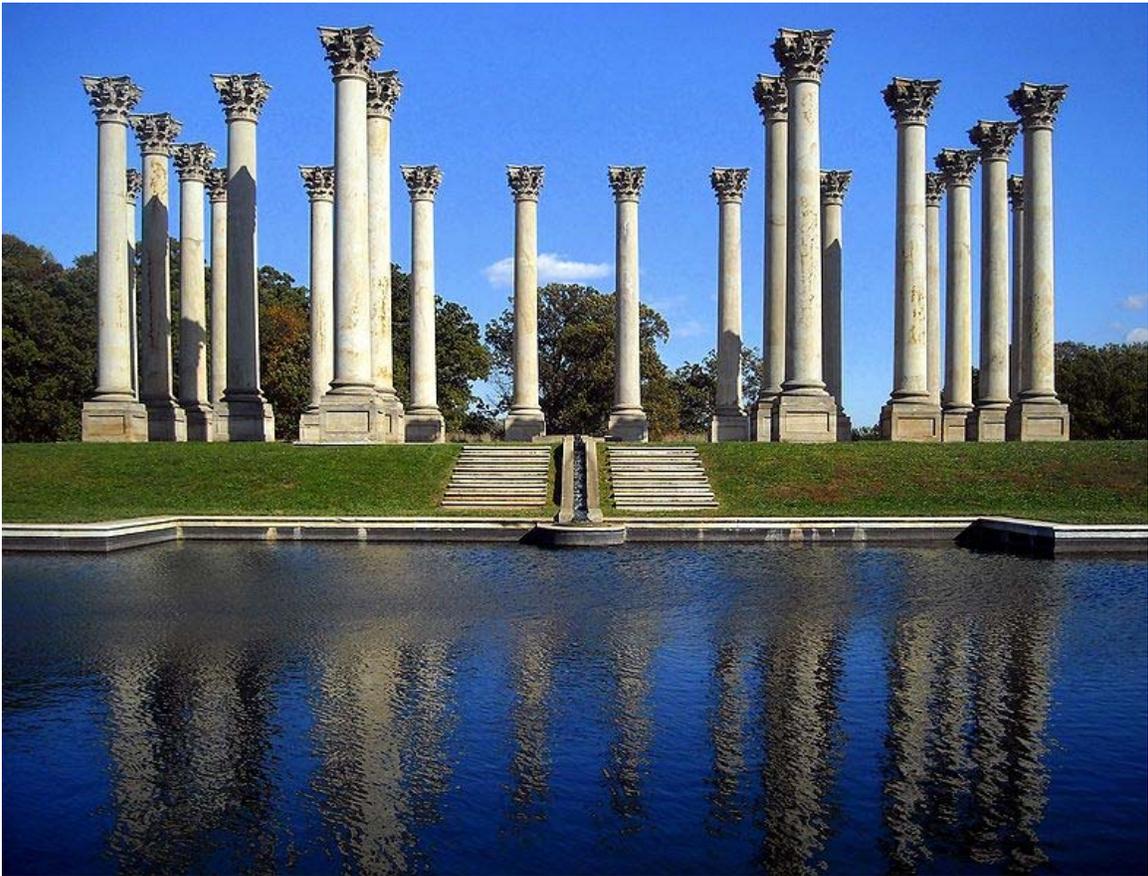


National Capitol Columns at the United States National Arboretum in Washington, D.C.

Marble columns with antique capitals in the Great Mosque of Kairouan also known as the Mosque of Uqba, city of Kairouan, Tunisia

A **column** in structural engineering is a vertical structural element that transmits, through compression, the weight of the structure above to other structural elements below. For the purpose of wind or earthquake engineering, columns may be designed to resist lateral forces. Other compression members are often termed "columns" because of the similar stress conditions. Columns are frequently used to support beams or arches on which the upper parts of walls or ceilings rest. In architecture "column" refers to such a structural element that also has certain proportional and decorative features. A column might also be a decorative or triumphant feature but need not be supporting any structure e.g. a statue on top.

Columns found at the Temple of Apollo in Delphi

In the architecture of ancient Egypt as early as 2600 BC the architect Imhotep made use of stone columns whose surface was carved to reflect the organic form of bundled reeds; in later Egyptian architecture faceted cylinders were also common.

Some of the most elaborate columns in the ancient world were those of Persia especially the massive stone columns erected in Persepolis. They included double-bull structures in their capitals. The Hall of Hundred Columns at Persepolis, measuring $70 \times 70$ meters was built by the Achaemenid king Darius I (524–486 BC). Many of the ancient Persian columns are standing, some being more than 30 meters tall.

The Greeks pioneered the use of the classical orders (Doric, Ionic, Corinthian) which was expanded by the Romans to include the Tuscan and Composite styles.

The impost (or pier) is the topmost member of a column. The bottom-most part of the arch, called the springing, rests on the impost.

## *Structure*



Modern column grid in a car park

Early columns were constructed of stone, some out of a single piece of stone, usually by turning on a lathe-like apparatus. Single-piece columns are among the heaviest stones used in architecture. Other stone columns are created out of multiple sections of stone, mortared or dry-fit together. In many classical sites, sectioned columns were carved with a center hole or depression so that they could be pegged together, using stone or metal pins. The design of most classical columns incorporates entasis (the inclusion of a slight outward curve in the sides) plus a reduction in diameter along the height of the column, so that the top is as little as 83% of the bottom diameter. This reduction mimics the parallax effects which the eye expects to see, and tends to make columns look taller and straighter than they are while entasis adds to that effect.

Modern columns are constructed out of steel, poured or precast concrete, or brick. They may then be clad in an architectural covering (or veneer), or left bare.

**Equilibrium, instability, and loads**
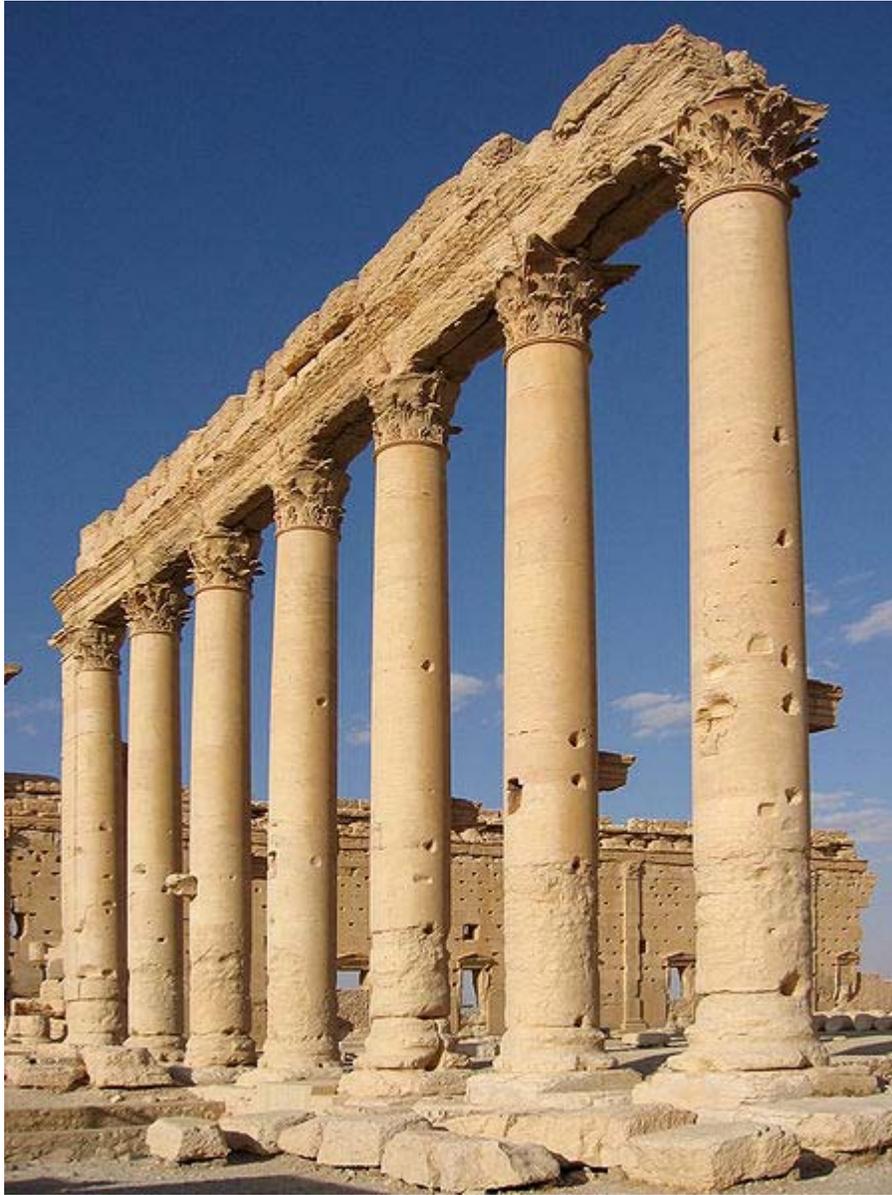


These are composed of stacked segments and finished in the Corinthian style (Temple of Bel, Syria)

As the axial load on a perfectly straight slender column with elastic material properties is increased in magnitude, this ideal column passes through three states: stable equilibrium, neutral equilibrium, and instability. The straight column under load is in stable equilibrium if a lateral force, applied between the two ends of the column, produces a small lateral deflection which disappears and the column returns to its straight form when the lateral force is removed. If the column load is gradually increased, a condition is reached in which the straight form of equilibrium becomes so-called neutral equilibrium, and a small lateral force will produce a deflection that does not disappear and the column remains in this slightly bent form when the lateral force is removed. The load at which

neutral equilibrium of a column is reached is called the critical or buckling load. The state of instability is reached when a slight increase of the column load causes uncontrollably growing lateral deflections leading to complete collapse.

For an axially loaded straight column with any end support conditions, the equation of static equilibrium, in the form of a differential equation, can be solved for the deflected shape and critical load of the column. With hinged, fixed or free end support conditions the deflected shape in neutral equilibrium of an initially straight column with uniform cross section throughout its length always follows a partial or composite sinusoidal curve shape, and the critical load is given by

$$f_{cr} \equiv \frac{\pi^2 E I_{min}}{L^2} \qquad (1)$$

where $E$ = elastic modulus of the material, $I_{min}$ = the minimal moment of inertia of the cross section, and $L$ = actual length of the column between its two end supports. A variant of (1) is given by

$$f_{cr} \equiv \frac{\pi^2 E_T}{(\frac{KL}{r})^2} \qquad (2)$$

| Buckled shape of column shown by dashed line | | | | | | |
|---|---|---|---|---|---|---|
| **Theoretical K value** | 0.5 | 0.7 | 1.0 | 1.0 | 2.0 | 2.0 |
| **Recommended design value K** | 0.65 | 0.80 | 1.2 | 1.0 | 2.10 | 2.0 |
| **End condition key** | | Rotation fixed and translation fixed | | | | |
| | | Rotation free and translation fixed | | | | |
| | | Rotation fixed and translation free | | | | |
| | | Rotation free and translation free | | | | |

Table showing values of K for structural columns of various end conditions (adapted from Manual of Steel Construction, 8th edition, American Institute of Steel Construction, Table C1.8.1)

where $r$ = radius of gyration of [column]cross-section which is equal to the square root of (I/A), $K$ = ratio of the longest half sine wave to the actual column length, and $KL$ = effective length (length of an equivalent hinged-hinged column). From Equation (2) it can be noted that the buckling strength of a column is inversely proportional to the square of its length.

When the critical stress, $F_{cr}$ ($F_{cr} = P_{cr}/A$, where $A$ = cross-sectional area of the column), is greater than the proportional limit of the material, the column is experiencing inelastic buckling. Since at this stress the slope of the material's stress-strain curve, $E_t$ (called the

tangent modulus), is smaller than that below the proportional limit, the critical load at inelastic buckling is reduced. More complex formulas and procedures apply for such cases, but in its simplest form the critical buckling load formula is given as Equation (3),

$$f_{cr} \equiv F_y - \frac{F_y^2}{4\pi^2 E}\left(\frac{KL}{r^2}\right) \qquad (3)$$

where $E_t$ = tangent modulus at the stress $F_{cr}$

A column with a cross section that lacks symmetry may suffer torsional buckling (sudden twisting) before, or in combination with, lateral buckling. The presence of the twisting deformations renders both theoretical analyses and practical designs rather complex.

Eccentricity of the load, or imperfections such as initial crookedness, decreases column strength. If the axial load on the column is not concentric, that is, its line of action is not precisely coincident with the centroidal axis of the column, the column is characterized as eccentrically loaded. The eccentricity of the load, or an initial curvature, subjects the column to immediate bending. The increased stresses due to the combined axial-plus-flexural stresses result in a reduced load-carrying ability.

Column elements are considered to be massive if minimal side dimension is equal or more than 400 mm. Massive columns have ability to increase concrete strength during long time period (even during exploitation period). Taking into account possible loads onto structure increase in future (and even threat of progressive failure - terroristic attacks, explosions etc.) - massive columns have advantage comparing with not ones. A little economy today has no sense as usual for future. Moreover relatively small sections are not technological for reinforced structures during their production. Balance between economy, mass of structures and so called "sustainable" construction is necessary.

## Extensions

When a column is too long to be built or transported in one piece, it has to be extended or spliced at the construction site. A reinforced concrete column is extended by having the steel reinforcing bars protrude a few inches or feet above the top of the concrete, then placing the next level of reinforcing bars to overlap, and pouring the concrete of the next level. A steel column is extended by welding or bolting splice plates on the flanges and webs or walls of the columns to provide a few inches or feet of load transfer from the upper to the lower column section. A timber column is usually extended by the use of a steel tube or wrapped-around sheet-metal plate bolted onto the two connecting timber sections.

## Foundations

A column that carries the load down to a foundation must have means to transfer the load without overstressing the foundation material. Reinforced concrete and masonry columns are generally built directly on top of concrete foundations. A steel column, when seated

on a concrete foundation, must have a base plate to spread the load over a larger area and thereby reduce the bearing pressure. The base plate is a thick rectangular steel plate usually welded to the bottom end of the column.

## *Classical orders*



Church of San Prospero, Reggio Emilia, Italy

The Roman author Vitruvius, relying on the writings (now lost) of Greek authors, tells us that the ancient Greeks believed that their Doric order developed from techniques for building in wood in which the earlier smoothed tree trunk was replaced by a stone cylinder.

## Doric order

The Doric order is the oldest and simplest of the classical orders. It is composed of a vertical cylinder that is wider at the bottom. It generally has neither a base nor a detailed capital. It is instead often topped with an inverted frustum of a shallow cone or a cylindrical band of carvings. It is often referred to as the masculine order because it is represented in the bottom level of the Colosseum and the Parthenon, and was therefore considered to be able to hold more weight. The height-to-thickness ratio is about 8:1. The shaft of a Doric Column is always fluted.

The Greek Doric, developed in the western Dorian region of Greece, is the heaviest and most massive of the orders. It rises from the stylobate without any base; it is from four to six times as tall as its diameter; it has twenty broad flutes; the capital consists simply of a banded necking swelling out into a smooth echinus, which carries a flat square abacus; the Doric entablature is also the heaviest, being about one-fourth the height column. The Greek Doric order was not used after c. 100 B.C. until its "rediscovery" in the mid-eighteenth century.

## Tuscan order

The Tuscan order, also known as Roman Doric, is also a simple design, the base and capital both being series of cylindrical disks of alternating diameter. The shaft is almost never fluted. The proportions vary, but are generally similar to Doric columns. Height to width ratio is about 7:1.

## Ionic order

The Ionic column is considerably more complex than the Doric or Tuscan. It usually has a base and the shaft is often fluted (it has grooves carved up its length). On the top is a capital in the characteristic shape of a scroll, called a volute, or scroll, at the four corners. The height-to-thickness ratio is around 9:1. Due to the more refined proportions and scroll capitals, the Ionic column is sometimes associated with academic buildings.
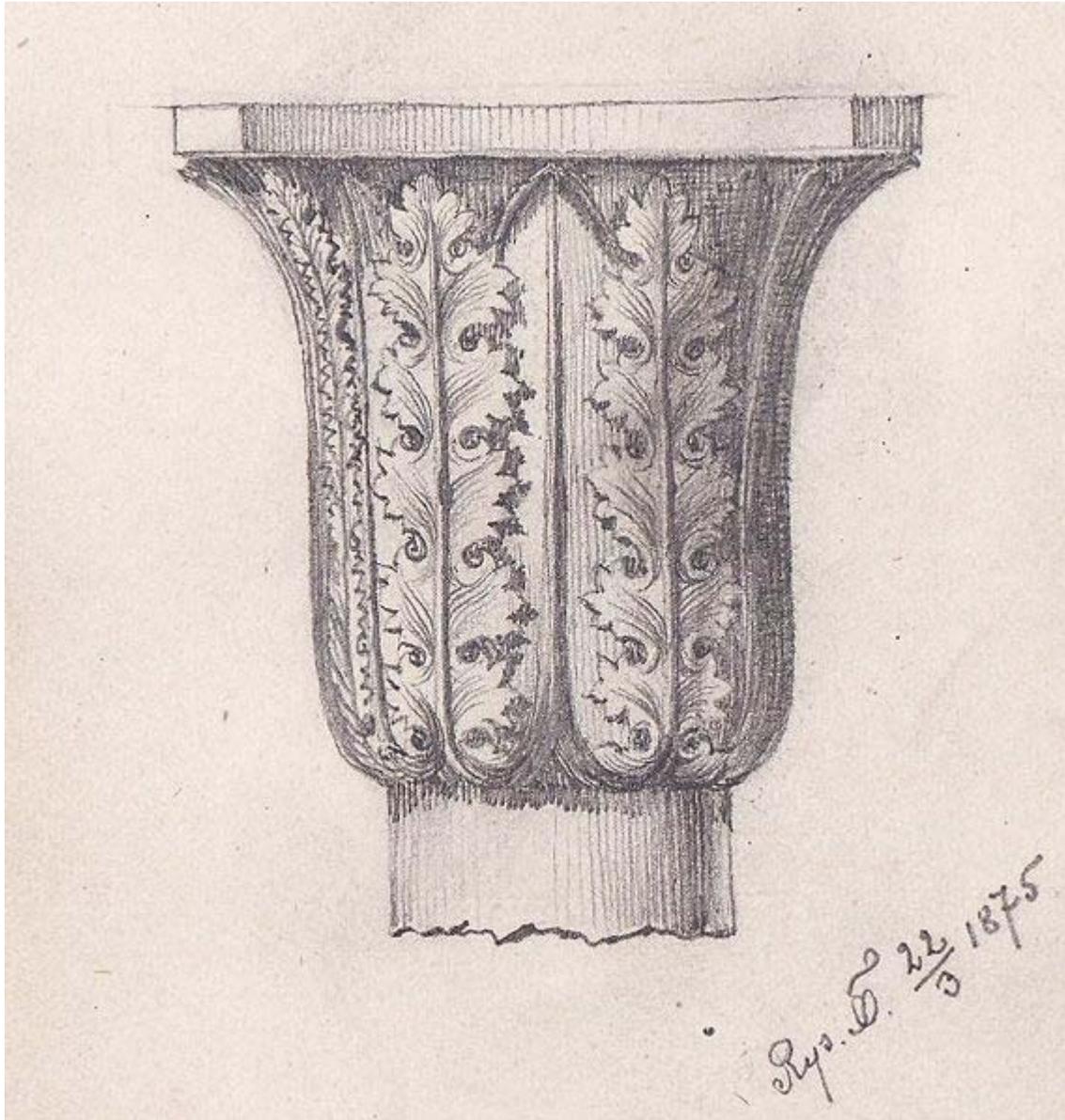
Ionic capital

## Corinthian order

The Corinthian order is named for the Greek city-state of Corinth, to which it was connected in the period. However, according to the architectural historian Vitruvius, the column was created by the sculptor Callimachus, probably an Athenian, who drew acanthus leaves growing around a votive basket. In fact, the oldest known Corinthian capital was found in Bassae, dated at 427 BC. It is sometimes called the feminine order because it is on the top level of the Colosseum and holding up the least weight, and also has the slenderest ratio of thickness to height. Height to width ratio is about 10:1.

## Composite order

The Composite order draws its name from the capital being a composite of the Ionic and Corinthian capitals. The acanthus of the Corinthian column already has a scroll-like element, so the distinction is sometimes subtle. Generally the Composite is similar to the Corinthian in proportion and employment, often in the upper tiers of colonnades. Height to width ratio is about 11:1 or 12:1.

# *Solomonic*

Capital of Solomonic Column

Solomonic columns were inventions of Baroque architects in Europe. They were not used in antiquity, but were called "Solomonic" by baroque architects because they were based on a description of columns in the great temple of King Solomon in the Old Testament. A Solomonic column begins on a base and ends in a capital, just like a classical column, but the shaft twists around the usual parameters of a column, producing a dramatic, serpentine effect of movement. The most famous use of Solomonic columns is in the baldacchino designed by Bernini for Saint Peter's Basilica in the Vatican City.

# Chapter- 5

# Catenary



The silk on a spider's web forming multiple elastic catenaries

In physics and geometry, the **catenary** is the curve that an idealised hanging chain or cable assumes when supported at its ends and acted on only by its own weight. The curve is the graph of the hyperbolic cosine function, and has a U-like shape, superficially similar in appearance to a parabola (though mathematically quite different). Its surface of revolution, the catenoid, is a minimal surface and is the shape assumed by a soap film bounded by two parallel circular rings.

## *History*

The word *catenary* is derived from the Latin word *catena,* which means "chain". Huygens first used the term *catenaria* in a letter to Leibniz in 1690. However, Thomas Jefferson is usually credited with the English word *catenary*. The curve is also called the "alysoid", "chainette", or, particularly in the material sciences, "funicular".

It is often stated that Galileo thought that the curve followed by a hanging chain is a parabola. A careful reading of his book *Two new sciences* shows this to be an oversimplification. Galileo discusses the catenary in two places; in the dialog of the Second Day he states that a hanging chain resembles a parabola. But later, in the dialog of the Fourth Day, he gives more details, and states that a hanging cord is approximated by a parabola, correctly observing that this approximation improves as the curvature gets smaller and is almost exact when the elevation is less than 45$^{\circ}$. That the curve followed by a chain is not a parabola was proven by Joachim Jungius (1587–1657) and published posthumously in 1669.

The application of the catenary to the construction of arches is due to Robert Hooke, who discovered it in the context of the rebuilding of St Paul's Cathedral, possibly having seen Huygens' work on the catenary. (Some much older arches are also approximate catenaries.)

In 1671, Hooke announced to the Royal Society that he had solved the problem of the optimal shape of an arch, and in 1675 published an encrypted solution as a Latin anagram in an appendix to his *Description of Helioscopes,* where he wrote that he had found "a true mathematical and mechanical form of all manner of Arches for Building." He did not publish the solution of this anagram in his lifetime, but in 1705 his executor provided it as *Ut pendet continuum flexile, sic stabit contiguum rigidum inversum,* meaning "As hangs a flexible cable so, inverted, stand the touching pieces of an arch."

In 1691 Gottfried Leibniz, Christiaan Huygens, and Johann Bernoulli derived the equation in response to a challenge by Jakob Bernoulli. David Gregory wrote a treatise on the catenary in 1697.

Euler proved in 1744 that the catenary is the curve which, when rotated about the *x*-axis, gives the surface of minimum surface area (the catenoid) for the given bounding circle.
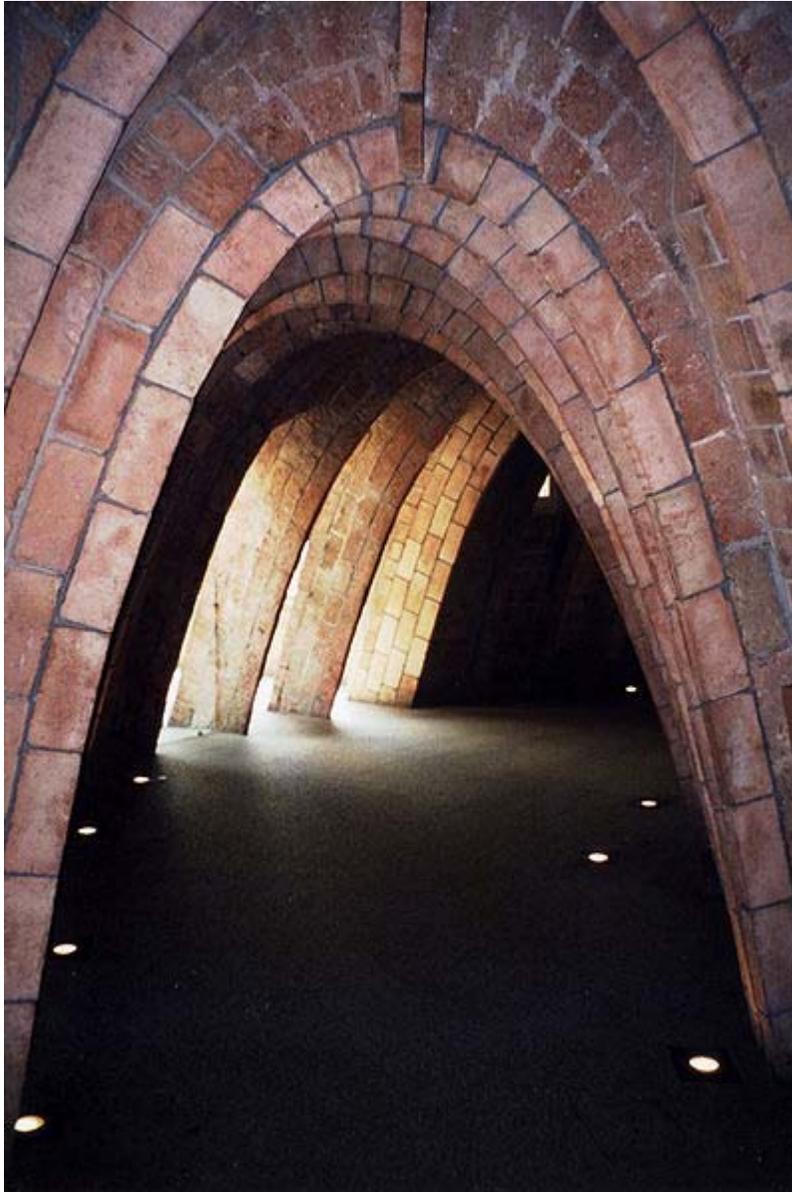
## *The inverted catenary arch*



Arch of Taq-i Kisra in Ctesiphon as seen today is roughly but not exactly a catenary



Gaudi's catenary model at Casa Milà

Arches under the roof of Gaudí's *Casa Milà*, Barcelona, Spain that are close to catenaries

Hooke discovered that the catenary is the ideal curve for an arch of uniform density and thickness which supports only its own weight. When the centerline of an arch is made to follow the curve of an up-side-down (i.e. inverted) catenary, the arch endures almost pure compression, in which no significant bending moment occurs inside the material.

The Sheffield Winter Garden is enclosed by a series of catenary arches

Catenary arches are often used in the construction of kilns. In this construction technique, the shape of a hanging chain of the desired dimensions is transferred to a form which is then used as a guide for the placement of bricks or other building material.

However the conditions for a catenary to be the ideal arch are almost never fulfilled: arches usually support more than their own weight, and on the rare occasions when they are freestanding they are sometimes not of uniform thickness.

The Gateway Arch (looking East) is a flattened catenary

Catenary arch kiln under construction over temporary form

The Gateway Arch in St. Louis, Missouri, United States is sometimes said to be an (inverted) catenary, but this is incorrect. It is close to a more general curve called a flattened catenary, with equation $y=A\cosh(Bx)$. (A catenary would have $AB=1$.) While a catenary is the ideal shape for a freestanding arch of constant thickness, the Gateway Arch is narrower near the top. According to the U.S. National Historic Landmark nomination for the arch, it is a "weighted catenary" instead. Its shape corresponds to the shape that a weighted chain, having lighter links in the middle, would form.

## *Simple suspension bridges*



In simple suspension bridges such as the Capilano Suspension Bridge, where the weight runs parallel to the cables, the cables follow a catenary curve.

Free-hanging chains follow the catenary curve, but suspension bridge chains or cables do not hang freely since they support the weight of the bridge. In most cases the weight of the cable is negligible compared with the weight being supported. When the force exerted is uniform with respect to the length of the chain, as in a simple suspension bridge, the result is a catenary.

When the force exerted is uniform with respect to horizontal distance, as in a suspension bridge, the result is a parabola.

When suspension bridges are constructed, the suspension cables initially sag as the catenary curve, before being tied to the deck below, and then gradually assume a parabolic curve as additional connecting cables are tied to connect the main suspension cables with the bridge deck below.



Golden Gate Bridge, San Francisco, California. Most suspension bridge cables follow a parabolic, not catenary curve.

## *Anchoring of marine objects*

The catenary form given by gravity is taken advantage of in its presence in heavy anchor rodes. An anchor rode (or anchor line) usually consists of chain and/or cable. Anchor rodes are used by ships, oilrigs, docks, wind turbines and other marine assets which must be anchored to the seabed.

Particularly with larger vessels, the catenary curve given by the weight of the rode presents a lower angle of pull on the anchor or mooring device. This assists the performance of the anchor and raises the level of force it will resist before dragging. With smaller vessels and in shallow water it is less effective.

The catenary curve in this context is only fully present in the anchoring system when the rode has been lifted clear of the seabed by the vessel's pull, as the seabed obviously affects its shape while it supports the chain or cable. There is also typically a section of rode above the water and thus unaffected by buoyancy, creating a slightly more complicated curve.

## *Mathematical description*

### Equation
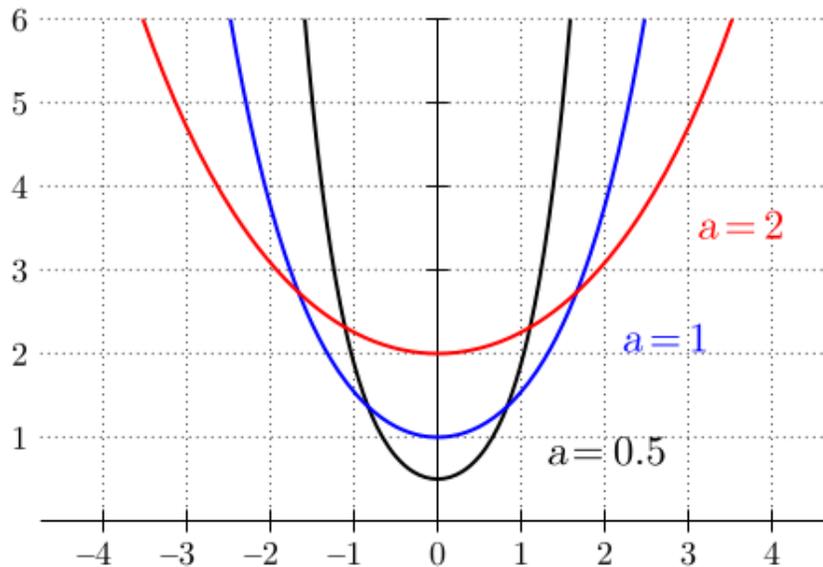


Catenaries for different values of $a$

The equation of a catenary in Cartesian coordinates has the form

$$y = a \cosh\left(\frac{x}{a}\right) = \frac{a}{2}\left(e^{x/a} + e^{-x/a}\right),$$

where cosh is the hyperbolic cosine function.

The Whewell equation for the catenary is

$$\tan \varphi = \frac{s}{a}.$$

Differentiating gives

$$\frac{d\varphi}{ds} = \frac{\cos^2 \varphi}{a}$$

and eliminating $\varphi$ gives the Cesàro equation:

$$\kappa = \frac{a}{s^2 + a^2}.$$

## Other properties

All catenary curves are similar to each other. Changing the parameter $a$ is equivalent to a uniform scaling of the curve.

A parabola rolled along a straight line traces out a catenary with its focus.

Square wheels can roll perfectly smoothly if the road has evenly spaced bumps in the shape of a series of inverted catenary curves. The wheels can be any regular polygon except a triangle, but the catenary must have parameters corresponding to the shape and dimensions of the wheels.

A charge in a uniform electric field moves along a catenary (which tends to a parabola if the charge velocity is much less than the speed of light $c$).

The surface of revolution with fixed radii at either end that has minimum surface area is a catenary revolved about the x-axis.

Over any horizontal interval [a,b], the ratio of the area under the caternary to its length equals a, independent of the interval selected. The catenary is the only plane curve other than a horizontal line with this property. Also, the geometric centroid of the area under a stretch of catenary is the midpoint of the perpendicular segment connecting the centroid of the curve itself and the x-axis.

## Analysis

We assume that the path followed by the chain is given parametrically by
$$\mathbf{r} = (x, y) = (x(s),\ y(s))$$ where $s$ represents arc length and $\mathbf{r}$ is the position vector.

This is the natural parameterization and has the property that $\dfrac{d\mathbf{r}}{ds}$ is the unit tangent vector,

**u**. The derivation of the curve for an optimal arch is similar except that the forces of tension become forces of compression and everything is inverted.

It is now possible to derive two equations which together define the shape of the curve and the tension of the chain at each point. This is done by a careful inspection of the various forces acting on a small segment of the chain and using the fact that these forces must be in balance if the chain is in static equilibrium.

First, let $\mathbf{T} = \mathbf{T}(s)$ be the force of tension as a function of $s$. The chain is flexible so it can only exert a force parallel to itself. Since tension is defined as the force that the chain exerts on itself, $\mathbf{T}$ must be parallel to the chain. In other words,

$$(1) \qquad \mathbf{T} = T\mathbf{u}$$

where $T$ is the magnitude of $\mathbf{T}$, a positive scalar function of $s$.

Second, let $\mathbf{G} = \mathbf{G}(s)$ be the external force per unit length acting on a small segment of a chain as a function of $s$. The forces acting on the segment of the chain between $s$ and $s + \Delta s$ are the force of tension $\mathbf{T}(s + \Delta s)$ at one end of the segment, the nearly opposite force $-\mathbf{T}(s)$ at the other end, and the external force acting on the segment which is approximately $\mathbf{G}\Delta s$. These forces must balance so

$$\mathbf{T}(s + \Delta s) - \mathbf{T}(s) + \mathbf{G}\Delta s \approx \mathbf{0}.$$

Divide by $\Delta s$ and take the limit as $\Delta s \to 0$ to obtain

$$(2) \qquad \frac{d\mathbf{T}}{ds} + \mathbf{G} = \mathbf{0}.$$

Note that, up till now, no assumptions have been made regarding the force $\mathbf{G}$, so equations (1) and (2) can be used as the starting point in the analysis of a flexible chain acting under any external force. The next step is to put in the specific expression for $\mathbf{G}$ and solve the resulting equations.

In this case, $\mathbf{G} = (0, -\lambda g)$ where the chain has constant mass per unit length $\lambda$ and the only external force acting on the chain is that of a uniform gravitational field $\mathbf{g} = (0, -g)$. So we have

$$\frac{d\mathbf{T}}{ds} = (0, \lambda g).$$

Integrating we get,

$$\mathbf{T} = (c, \lambda g s + d).$$

Note that at the minimum the curve is horizontal and
$$\mathbf{T} = T\mathbf{u} = T(1,0) = (T,0) = (c, \lambda g s + d).$$ So $c$ is the tension of the chain at its lowest point this point occurs at $s = -d/\lambda g$. The point from which $s$ is measured is arbitrary, so pick this point to be the minimum, giving $d = 0$. The equation becomes

$$\mathbf{T} = (c, \lambda g s).$$

Note that the horizontal component of the tension is a constant.

From here, we can continue the derivation in two ways.

**Alternative 1**

If $\varphi$ is the tangential angle of the curve then $\mathbf{T}$ is parallel to $(1, \tan\varphi)$ so

$$\tan\varphi = \frac{\lambda g s}{c}.$$

Write $a = \dfrac{c}{\lambda g}$ to combine constants and obtain the Whewell equation for the curve,

$$\tan\varphi = \frac{s}{a}.$$

In general, parametric equations can be obtained from a Whewell equation by integrating:

$$x = \int \cos\varphi \, ds$$
$$y = \int \sin\varphi \, ds$$

To find these integrals, make the substitution $\tan\varphi = \sinh u$ (or $\varphi = \operatorname{gd} u$ where gd is the Gudermannian function).

Then $s = a \sinh u$ and

$$x = \int \cos\varphi ds = \int \operatorname{sech} u \, a \cosh u \, du = a \int du = au + \alpha$$
$$y = \int \sin\varphi ds = \int \tanh u \, a \cosh u \, du = a \int \sinh u \, du = a \cosh u + \beta.$$

We can eliminate u to obtain

$$y = a \cosh \frac{x - \alpha}{a} + \beta$$

where $\alpha$ and $\beta$ are constants to be determined, along with $a$, by the boundary conditions of the problem. Usually these conditions include two points from which the chain is being suspended and the length of the chain.

**Alternative 2**

From

$$\mathbf{T} = T\mathbf{u} = T\left(\frac{dx}{ds}, \frac{dy}{ds}\right) = (c, \lambda gs)$$

$$\frac{dy}{dx} = \frac{dy}{ds} \bigg/ \frac{dx}{ds} = \frac{\lambda gs}{c} = \frac{s}{a}$$

where $a = \dfrac{c}{\lambda g}$, same as before. Then

$$\frac{dx}{ds} = 1 \bigg/ \frac{ds}{dx} = \frac{1}{\sqrt{1 + \left(\dfrac{dy}{dx}\right)^2}} = \frac{a}{\sqrt{a^2 + s^2}}$$

and

$$\frac{dy}{ds} = \frac{dy}{dx} \cdot \frac{dx}{ds} = \frac{s}{\sqrt{a^2 + s^2}}.$$

The integrals of the right hand sides of these equations can be found using standard techniques giving

$$x = a \ \text{arcsinh}(s/a) + \alpha, \quad y = \sqrt{a^2 + s^2} + \beta.$$

Isolating $s$ in the first equation and using the result to substitute $s$ in the second equation gives

$$y = a \cosh \frac{x - \alpha}{a} + \beta$$

as before, α and β are constants to be determined, along with $a$, by the boundary conditions of the problem, which is exact the same result as that obtained with Alternative 1.

## *Variations*

### Elastic catenary

In an elastic catenary, the cable replaced by a spring and is no longer assumed to be of fixed density, but is allowed to stretch in accordance with Hooke's Law. In this case, the mass per unit length is no longer constant but can be given as

$$\lambda = \frac{\lambda_0}{1 + \epsilon T}$$

where $\lambda_0$ is the mass per unit length for the chain in its relaxed state and ε is the spring constant. As in the earlier derivation,

$$\frac{d\mathbf{T}}{ds} = (0, \lambda g)$$.

So the horizontal component of $\mathbf{T}$, $T \cos \varphi$ is a constant c. Putting this into the equation for density produces

$$\lambda = \frac{\lambda_0}{1 + c\epsilon \sec \varphi}$$.

Then the equation for the vertical component of $\mathbf{T}$ is

$$\frac{d}{ds}(T \sin \varphi) = c\frac{d}{ds}(\tan \varphi) = \frac{g\lambda_0}{1 + c\epsilon \sec \varphi}$$,

or, combining constants,

$$\frac{d}{ds}(\tan \varphi) = \frac{1}{a + b \sec \varphi}$$.

Using the substitution $\tan \varphi = \sinh u$ gives

$$\frac{d}{ds}(\sinh u) = \cosh u \frac{du}{ds} = \frac{1}{a + b \cosh u}$$

or

$$\cosh u(a + b\cosh u) = \frac{ds}{du}.$$

Parametric equations can be obtained by integrating:

$$x = \int \cos\varphi\, ds = \int \operatorname{sech} u \cosh u(a + b\cosh u)\,du = \int (a + b\cosh u)\,du = au + b\sinh u + \alpha,$$

$$y = \int \sin\varphi\, ds = \int \tanh u \cosh u(a + b\cosh u)\,du = \int \sinh u(a + b\cosh u)\,du = a\cosh u + \tfrac{b}{2}\sinh^2 u + \beta.$$

When $b = 0$, corresponding to a completely inelastic cable, this is simply the catenary. When $a = 0$, corresponding to the case there the cable essentially has length 0 in its relaxed state, similar to a Slinky, this is a parabola. When $a$ and $b$ are both $>0$ then the curve is intermediate between a catenary and a parabola.

## Equal resistance catenary

In an equal resistance catenary, cable is strengthened according to the magnitude of the tension at each point, so its resistance to breaking is constant along its length. Assuming that the strength of the cable is proportional to its density, the mass per unit length can be given as

$$\lambda = \lambda_r T$$

where $\lambda_r$ is the mass per unit length per unit of tension force required for the chain to resist breaking. As in the earlier derivation,

$$\frac{d\mathbf{T}}{ds} = (0, \lambda g).$$

So the horizontal component of $\mathbf{T}$, $T\cos\varphi$ is a constant c. Putting this into the equation for density produces

$$\lambda = \lambda_r c \sec\varphi.$$

Then the equation for the vertical component of $\mathbf{T}$ is

$$\frac{d}{ds}(T\sin\varphi) = c\frac{d}{ds}(\tan\varphi) = g\lambda_r c \sec\varphi,$$

or, combining constants,

$$\frac{d}{ds}(\tan\varphi) = \frac{1}{a}\sec\varphi.$$

or

$$\frac{d}{ds}\left(\frac{dy}{dx}\right) = \frac{1}{a}\frac{ds}{dx}.$$

Multiplying both sides by *ds* / *dx* gives

$$\frac{d^2y}{dx^2} = \frac{1}{a}\left(\frac{ds}{dx}\right)^2 = \frac{1}{a}\left[1 + \left(\frac{dy}{dx}\right)^2\right].$$

This can be reduced to a differential equation of degree one using separation of variables to obtain

$$\arctan\frac{dy}{dx} = \frac{x}{a} - \alpha$$

or

$$\frac{dy}{dx} = \tan\left(\frac{x}{a} - \alpha\right).$$

Another integration produces

$$y = -a\ln\cos\left(\frac{x}{a} - \alpha\right) + \beta.$$

## Towed cables

Instead of gravity, we assume we have a cylindrical cable that is acted on by drag forces due to the movement of some surrounding fluid (e.g. air or water). The velocity relative to the cable is assumed to be a constant $\mathbf{V} = (0, -v)$. (Velocity is assumed to be vertical here to preserve similarities with the gravitational case.) To compute the force due to drag, write $\mathbf{V} = \mathbf{V}_u + \mathbf{V}_n$ where $\mathbf{V}_u$ and $\mathbf{V}_n$ respectively are the components parallel to and orthogonal to the cable. The cable is assumed to be smooth so the force on the cable due to $\mathbf{V}_u$ is taken to be negligible. The force acting on the cable, following the Drag equation is

$$\mathbf{G} = -c|\mathbf{v}_n|^2\mathbf{n}$$

where *c* is a constant depending on the density of the fluid, the diameter of the cable, and the Drag coefficient. If $\mathbf{n} = (-\sin\varphi, \cos\varphi)$ denotes the unit normal vector, then

$$\mathbf{v}_n = \mathbf{v} \cdot \mathbf{n}\,\mathbf{n} = -\cos\varphi\,\mathbf{n}$$

So

$$\mathbf{G} = -c\cos^2\varphi\,\mathbf{n}$$

From equations (1) and (2) above,

$$\frac{d\mathbf{T}}{ds} = \frac{dT}{ds}\mathbf{u} + T\frac{d\mathbf{u}}{ds} = \frac{dT}{ds}\mathbf{u} + T\frac{d\varphi}{ds}\mathbf{n} = c\cos^2\varphi\,\mathbf{n}$$

Setting the coefficients of $\mathbf{u}$ and $\mathbf{n}$ equal produces

$$\frac{dT}{ds} = 0,\ T\frac{d\varphi}{ds} = c\cos^2\varphi$$

So T is a constant in this case and combining constants in the second equation gives

$$\frac{d\varphi}{ds} = \frac{\cos^2\varphi}{a}$$

which is one of the equations for the catenary given above. This is a case where a different expression for the force acting on the chain/cable produce the same curve but a different expression for tension.

In applications, the force of gravity and additional terms in the force due to drag may be added to the expression for force, yielding equations that must be solved numerically.
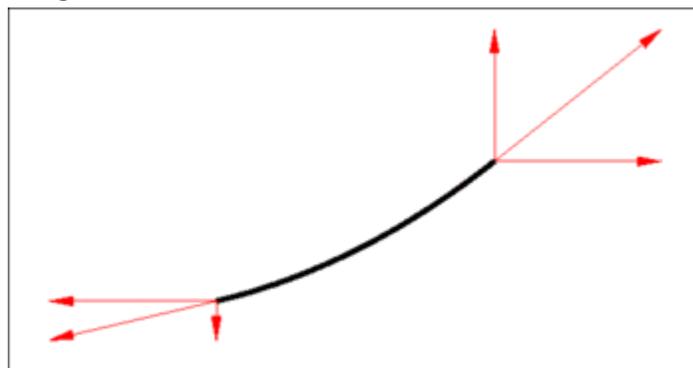
## *Alternative analysis*



Figure 1: The forces acting on the two extremes of a segment of a catenary decomposed into horizontal and vertical components

The forces acting on a segment of catenary curve are shown in the figure at right.

The vector sum of the forces acting on the segment from the two extremities and from the gravitational force must be zero. As the gravitational force is directed downwards the horizontal components of the forces acting on the extremes must have the same magnitude. As this is true for any segment of the catenary this is a fixed constant for the whole of the catenary. Denoting this constant with $f$ one gets that the vertical component of the force at the left extreme $x_1$ is $-f \, y'(x_1)$ and at the right extreme $x_2$ is $f \, y'(x_2)$ The path length of the curve representing a function $y(x)$ with $x$ varying from $x_1$ to $x_2$ is

$$\int_{x_1}^{x_2} \sqrt{1 + y'^2} dx$$

If $g$ is the gravitational constant and $\rho$ is the mass per length unit of the chain the

gravitational force acting on the arc from $x_1$ to $x_2$ is $\quad g\rho \int_{x_1}^{x_2} \sqrt{1 + y'^2} dx$

This force must be compensated by the vertical components of the forces acting on the two extremes of the arc, i.e.

$$f \left( y'(x_2) - y'(x_1) \right) = g\rho \int_{x_1}^{x_2} \sqrt{1 + y'^2} dx \, (1)$$

Denoting the constant ratio $\dfrac{f}{g\rho}$ with $a$ and taking the derivative of equation (**1**) with respect to the upper limit of the integral, i.e. with respect to $x_2$, one gets

$$y'' = \frac{1}{a}\sqrt{1 + y'^2}$$

Denoting $y'$ with $z$ this equation takes the form

$$z' = \frac{dz}{dx} = \frac{1}{a}\sqrt{1 + z^2}$$

what means that for the inverse function $x(z)$ one has

$$\frac{dx}{dz} = \frac{a}{\sqrt{1 + z^2}}$$

which is integrate to

$$x = a \ \sinh^{-1}(z) + x_0$$

where $x_0$ is the constant of integration or equivalently

$$z = y' = \sinh(\frac{x - x_0}{a})$$

Again integrating with respect to $x$ one gets

$$y = a \ \cosh(\frac{x - x_0}{a}) \ + \ y_0 \ (2)$$

where $y_0$ is the second constant of integration

The lowest point of this curve has the coordinates $( \ x_0 \ , \ y_0 + a)$

The length of the curve given by (2) from $x = x_1$ to $x = x_2$ is

$$l = \int_{x_1}^{x_2} \sqrt{1 + y'^2} dx = \left[ a \sinh \frac{x - x_0}{a} \right]_{x_1}^{x_2} \ (3)$$

This family of solutions is parametrized with the 3 parameters $a, \ x_0, \ y_0$. For any concrete case these 3 parameters must be computed to fit the boundary value conditions. In a typical case the form of a chain having a given length l and being attached in two fixed point with the coordinates $x_1, \ y_1$ and $x_2, \ y_2$ relative a vertical coordinate system should be computed.

This means that $a, \ x_0, \ y_0$ have to be determined such that

$$y_1 = a \ \cosh(\frac{x_1 - x_0}{a}) \ + \ y_0 \ (4)$$
$$y_2 = a \ \cosh(\frac{x_2 - x_0}{a}) \ + \ y_0 \ (5)$$
$$l = a \left( \sinh \frac{x_2 - x_0}{a} \ - \ \sinh \frac{x_1 - x_0}{a} \right) (6)$$

Setting

$$x_m = \frac{x_2 + x_1}{2}$$
$$\Delta x = \frac{x_2 - x_1}{2}$$

subtracting (4) from (5) and then dividing with $a$ one gets

$$\frac{y_2 - y_1}{a} = \cosh\left(\frac{x_m - x_0}{a} + \frac{\Delta x}{a}\right) - \cosh\left(\frac{x_m - x_0}{a} - \frac{\Delta x}{a}\right) = 2\sinh\frac{x_m - x_0}{a}\sinh\frac{\Delta x}{a} \quad (7)$$

For any given values $x_1$, $y_1$, $x_2$, $y_2$, $a$ one can determine $\sinh\dfrac{x_m - x_0}{a}$ from (7)

When $\sinh\dfrac{x_m - x_0}{a}$ has been determined $\dfrac{x_m - x_0}{a}$ is computed by solving a quadratic equation.

In case $y_1 = y_2$, i.e. in the case that the two attachment points are at the same heigth, one has that $x_0 = x_m$ and that the length is $l = 2\,a\left(\sinh\dfrac{\Delta x}{a}\right)$

With $x_0$ known (4) or (5) can subsequently be used to determine $y_0$.

Having determined $x_0$ with the algorithm just described the curve length $l$ corresponding to the selected $a$ value can be computed from (6). With an iterative algorithm the $a$ value that corresponds to a certain curve length $l$ can finally be derived.
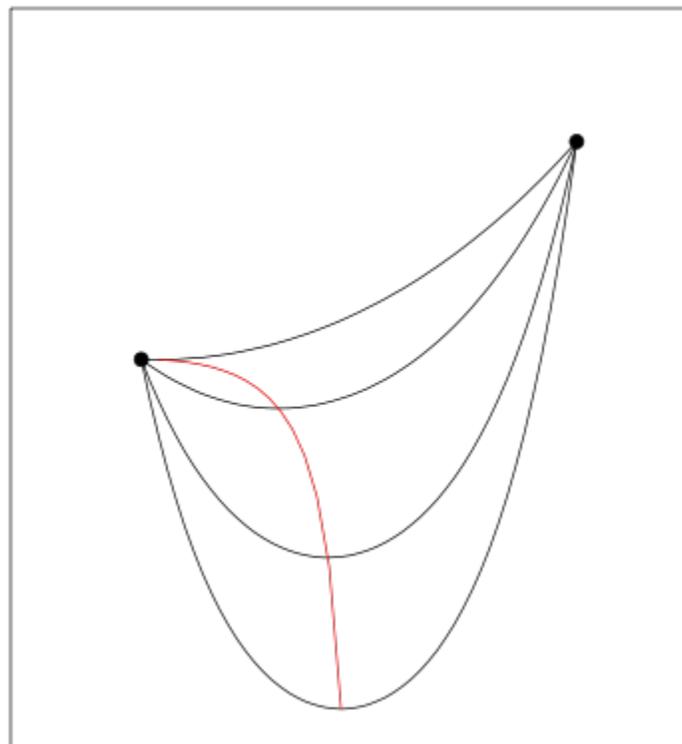


Figure 2:The red line corresponds to parameters X_0 and Y_0 + a determined with the algorithm described above for different values of a

From figure 1 it is further clear that the tension of the chain at any point $(x, y)$ is

$$f\sqrt{1 + y'^2} = f\cosh\frac{x - x_0}{a} = f\frac{y - y_0}{a}$$ where $f = a\,g\,\rho$ is the magnitude of
the constant horizontal force component

If the mass density $\rho$ is not constant but varies depending on some law the resulting differential equation will in most cases not have a closed form analytic solution. But the resulting curve can still be determined with arbitrary accuracy by the numerical integration of the differential equations

$$y' = z$$
$$z' = \frac{g}{f}\,\rho(z)\sqrt{1 + z^2}$$

Given any initial values for $y(x1)$ and $z(x1)$ and any value for the parameter $f$ these differential equations can be propagated to $x = x_2$ with $\rho$ specified as any function of the state variable $z$. The free parameters to be iteratively adjusted to fit the boundary constraints are now $z(x1)$ and $f$. They can for example be adjusted iteratively such that $y(x2) = y_2$ where $(x_2, y_2)$ is the second attachment point. This leaves an additional degree of freedom for the two parameters that can be used to get the correct length of the curve.

An example is the "elastic catenary" for which the force

$$f\sqrt{1 + y'^2} = f\sqrt{1 + z^2}$$

stretches the material with a factor

$$1 + \epsilon f\sqrt{1 + z^2}$$

where $\varepsilon$ is an elasticity coefficient and that therefore the mass density (mass per unit length) is

$$\rho = \frac{\rho_0}{1 + \epsilon f\sqrt{1 + z^2}}$$

where $\rho_0$ is the mass density of the material in the absence of stress.

A case where a closed form mathematical solution is possible is the case of "the equal resistance catenary" where the mass density (mass per unit length) is proportional to the force $f\sqrt{1 + y'^2} = f\sqrt{1 + z^2}$, i.e.

$$\rho = \rho_0\sqrt{1 + z^2}$$

where $\rho_0$ is the density at the lowest point

Setting $a = \dfrac{f}{g\rho_0}$ the differential equations now take the form

$$y' = z$$
$$z' = \frac{1}{a}\left(1 + z^2\right)$$

what means that for the inverse function $x(z)$ one has

$$\frac{dx}{dz} = \frac{a}{1 + z^2}$$

which is integrate to

$$x = a \ \arctan(z) + x_0$$

where $x_0$ is the constant of integration or equivalently

$$z = y' = \tan(\frac{x - x_0}{a})$$

where $x$ is constraint to an interval $x_0 - a\,\dfrac{\pi}{2} < x < x_0 + a\,\dfrac{\pi}{2}$

Again integrating with respect to $x$ one gets

$$y = y_0 \ - a \ln\left(\cos\left(\frac{x - x_0}{a}\right)\right)$$

where $y_0$ is the second constant of integration.

As $a \ \sinh \dfrac{C}{a} \ \to \ \infty$ when $a \ \to \ 0$ for any constant $C$ it follows from (**6**) that by making a catenary that is fixed at two points sufficiently long the constant horizontal force component $f$ can be made arbitrarily small. For this generalized "catenary of equal resistance" this is no more true, as $a$ must be larger then $\dfrac{|x - x_0|}{\frac{\pi}{2}}$ for any $x$ between $x_1$ and $x_2$ the positions of the two attachment points and the density $\rho_0$ at the lowest point impose a lower limit for the fixed horizontal force component $f$

## Alternative analysis "towed cables"

The following figure illustrates a segment of a cable that is fixed in both ends and exposed to drag.
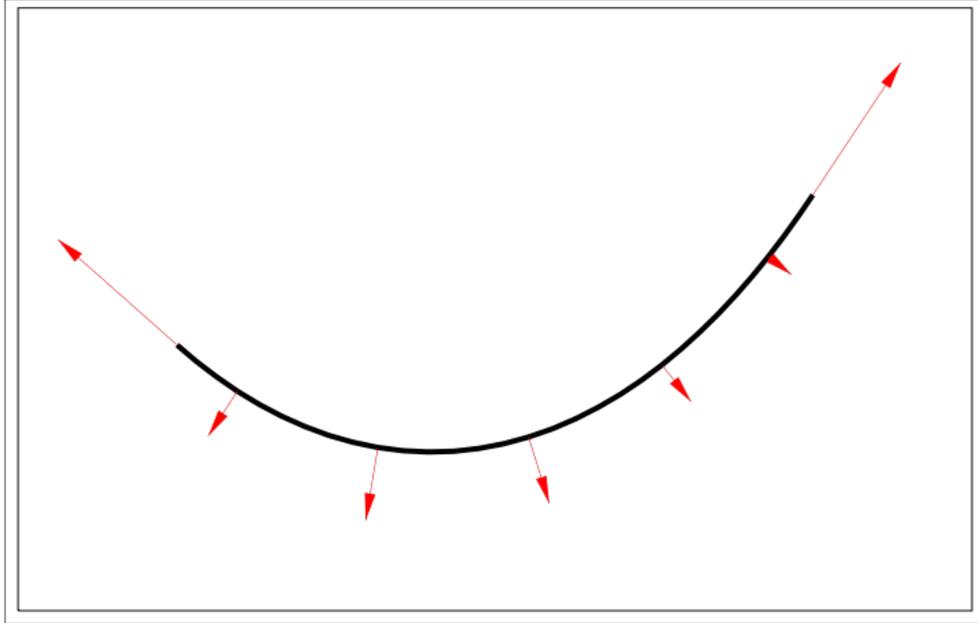


The forces acting on a cable subject to drag. The medium causing the drag is moving downwards. The drag force is orthogonal to the cable and the forces acting on the two extremities of the segment compensate the net drag force on the segment

The velocity relative to the cable is assumed to be constant and the coordinate system is selected such that this velocity is in the -y direction, i.e. $\mathbf{V} = (0, -v)$. To compute the force due to drag, write $\mathbf{V} = \mathbf{V}_u + \mathbf{V}_n$

where $\mathbf{V}_u$ and $\mathbf{V}_n$ respectively are the components parallel to and orthogonal to the cable. The cable is assumed to be smooth so the force on the cable due to $\mathbf{V}_u$ is taken to be negligible. The force acting on the cable, per unit length, following the Drag equation is therefore

$$\mathbf{G} = f(x)\mathbf{n}$$

with

$$f(x) = c\, v^2\, n_y{}^2 \quad (1)$$

where $c$ is a constant depending on the density of the fluid, the diameter of the cable, and the Drag coefficient and $\mathbf{n} = (n_x,\ n_y)$ denotes the unit normal vector.

For any curve $y(x)$ the tangent (unit vector) is

$$(t_x \ , \ t_y) = \frac{(1 \ , \ y')}{\sqrt{1 + y'^2}} \, (2)$$

and the normal (unit vector) is

$$(n_x \ , \ n_y) = \frac{(y' \ , \ -1)}{\sqrt{1 + y'^2}} \, (3)$$

From (**1**) and (**3**) follows that

$$f(x) = c \, v^2 \, \frac{1}{1 + y'^2} \, (4)$$

From (**3**) and (**4**) follows that the x-component of the total force on the segment of the curve from $x = x_1$ to $x = x_2$ is

$$F_x = \int_{x_1}^{x_2} f(x) \, n_x \, \sqrt{1 + y'^2} dx = c \, v^2 \int_{x_1}^{x_2} \frac{y'}{1 + y'^2} \, dx \, (5)$$

and the component in the y-direction is

$$F_y = \int_{x_1}^{x_2} f(x) \, n_y \, \sqrt{1 + y'^2} dx = c \, v^2 \int_{x_1}^{x_2} \frac{-1}{1 + y'^2} \, dx \, (6)$$

If now

$$y' = \sinh(\frac{x - x_0}{a})$$

one has that

$$1 + y'^2 = \cosh^2(\frac{x - x_0}{a})$$

and from (**2**),(**5**) and (**6**) that

$$F_x = c \; v^2 \int_{x_1}^{x_2} \frac{\sinh\left(\frac{x-x_0}{a}\right)}{\cosh^2\left(\frac{x-x_0}{a}\right)} \, dx = -\left[\frac{c \; v^2 \; a}{\cosh\left(\frac{x-x_0}{a}\right)}\right]_{x_1}^{x_2} =$$

$$\qquad\qquad (7)$$

$$-\left[\frac{c \; v^2 \; a}{\sqrt{1+y'^2}}\right]_{x_1}^{x_2} = -c \; v^2 \; a \; (t_x(x_2) - t_x(x_1))$$

$$F_y = c \; v^2 \int_{x_1}^{x_2} \frac{-1}{\cosh^2\left(\frac{x-x_0}{a}\right)} \, dx = -\left[\frac{c \; v^2 \; a \; \sinh\left(\frac{x-x_0}{a}\right)}{\cosh\left(\frac{x-x_0}{a}\right)}\right]_{x_1}^{x_2} =$$

$$\qquad\qquad (8)$$

$$-\left[\frac{c \; v^2 \; a \; y'}{\sqrt{1+y'^2}}\right]_{x_1}^{x_2} = -c \; v^2 \; a \; (t_y(x_2) - t_y(x_1))$$

If the now the force in the cable is

$$F = c \; v^2 \; a$$

the force at the right extreme of the cable segment is

$$c \; v^2 \; a \; (t_x(x_2) \; , \; t_y(x_2))$$

and at the left extreme

$$-c \; v^2 \; a \; (t_x(x_1) \; , \; t_y(x_1))$$

From **(7)** and **(8)** follows that the vector sum of these forces is precisely the force needed to counter act the forces on the segment caused by the drag

# Chapter- 6

# Arch (Structural Element)
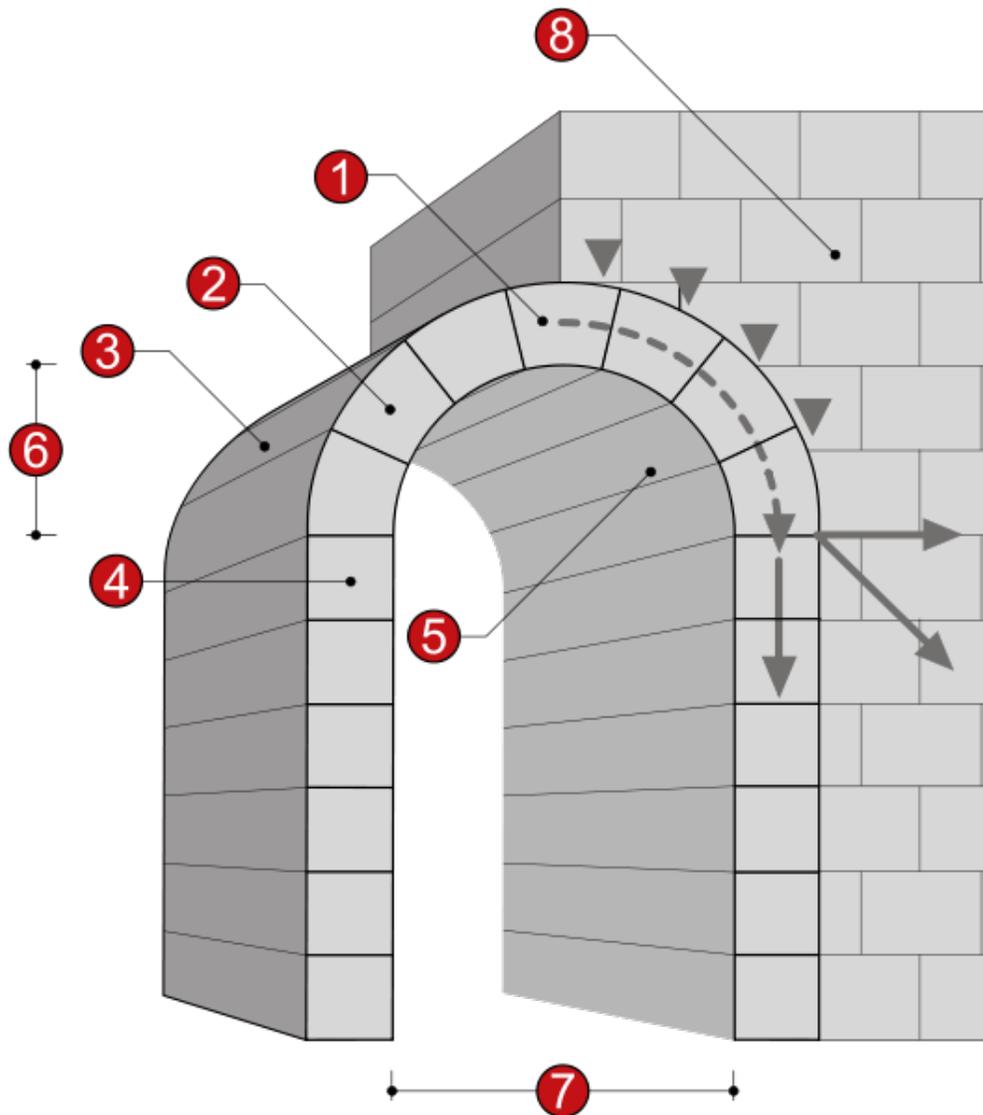


A masonry arch
1. Keystone 2. Voussoir 3. Extrados 4. Impost 5. Intrados 6. Rise 7. Clear span
8. Abutment

An **arch** is a structure that spans a space while supporting weight (e.g. a doorway in a stone wall). Arches appeared as early as the 2nd millennium BC in Mesopotamian brick architecture and their systematic use started with the Ancient Romans who were the first to apply the technique to a wide range of structures.

The semicircular arch was followed in Europe by the pointed Gothic arch or ogive whose centreline more closely followed the forces of compression and which was therefore stronger. The semicircular arch can be flattened to make an elliptical arch as in the Ponte Santa Trinita. The parabolic and catenary arches are now known to be the theoretically strongest forms. Parabolic arches were introduced in construction by the Spanish architect Antoni Gaudí, who admired the structural system of Gothic style, but for the buttresses, which he termed "architectural crutches". The catenary and parabolic arches carry all horizontal thrust to the foundation and so do not need additional elements.



Arch of Constantine, Rome, Italy commemorating a victory by Constantine I in 312 AD

The horseshoe arch is based on the semicircular arch, but its lower ends are extended further round the circle until they start to converge. The first known built horseshoe arches are known from Aksum (modern day Ethiopia and Eritrea) from around the 3rd–4th century, around the same time as the earliest contemporary examples in Roman Syria, suggesting either an Aksumite or Syrian origin for the type of arch.

Roman arch architecture in Ostia Antica, Italy



The Arc de Triomphe, Paris; a 19th-century triumphal arch modeled on the classical Roman design

True arches, as opposed to corbel arches, were known by a number of civilizations in the Ancient Near East, the Levant, and Mexico, but their use was infrequent and mostly confined to underground structures such as drains where the problem of lateral thrust is greatly diminished. A rare exception is the bronze age arched city gate of Ashkelon, Israel, dating to ca. 1850 BC. An early example of a voussoir arch appears in the Greek Rhodes Footbridge. In 2010, a robot discovered a long arch-roofed passageway underneath the Pyramid of Quetzalcoatl which stands in the ancient city of Teotihuacan north of Mexico City, dated to around 200 AD.

The ancient Romans learned the arch from the Greeks and Etruscans, refined it and were the first builders to tap its full potential for above ground buildings:

*The Romans were the first builders in Europe, perhaps the first in the world, fully to appreciate the advantages of the arch, the vault and the dome.*
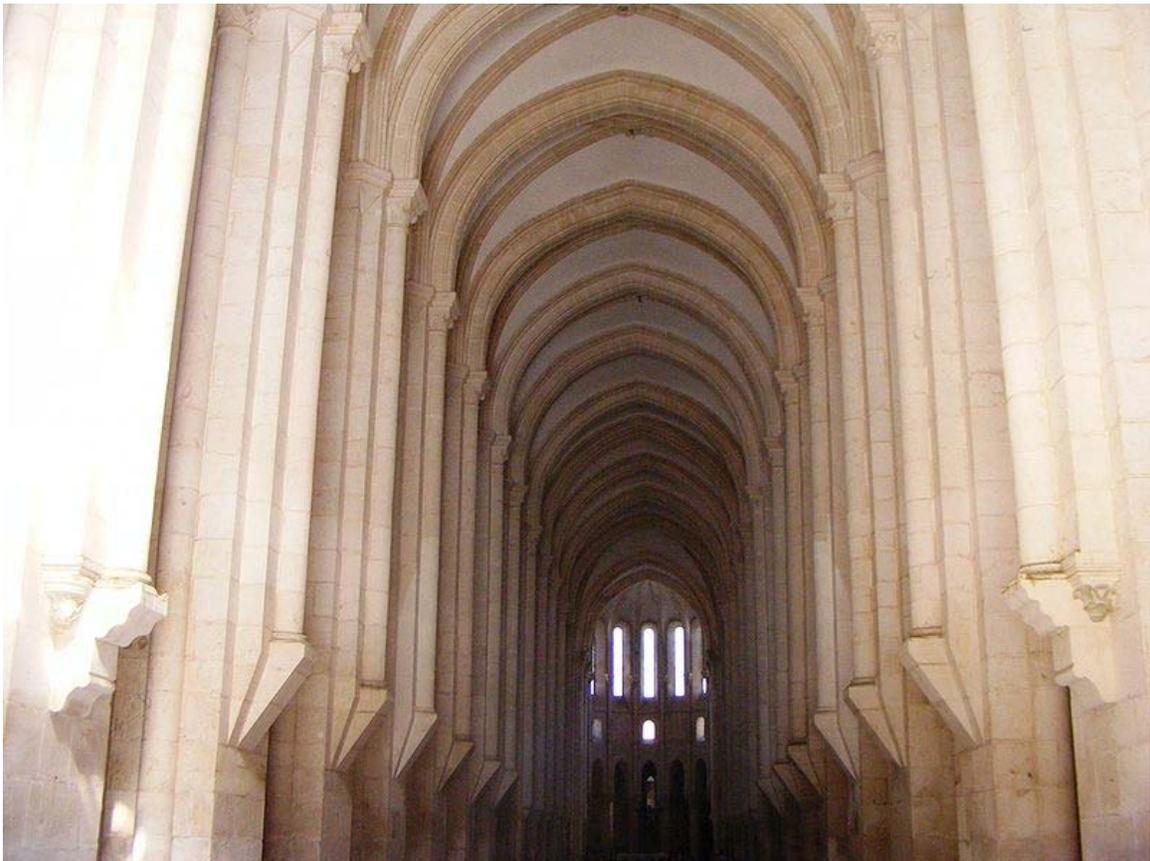


Arches in the nave of the church in monastery of Alcobaça, Portugal

Throughout the Roman empire, their engineers erected arch structures such as bridges, aqueducts, and gates. They also introduced the triumphal arch as a military monument. Vaults began to be used for roofing large interior spaces such as halls and temples, a function which was also assumed by domed structures from the 1st century BC onwards.

The segmental arch was first built by the Romans who realized that an arch in a bridge did not have to be a semicircle, such as in Alconétar Bridge or Ponte San Lorenzo. They were also routinely used in house construction as in Ostia Antica (see picture).



Catenary arches inside Casa Milà in Barcelona, Spain by Antoni Gaudí

## *Construction*

An arch requires all of its elements to hold it together, raising the question of how an arch is constructed. One answer is to build a frame (historically, of wood) which exactly follows the form of the underside of the arch. This is known as a centre or centring. The voussoirs are laid on it until the arch is complete and self-supporting. For an arch higher than head height, scaffolding would in any case be required by the builders, so the scaffolding can be combined with the arch support. Occasionally arches would fall down when the frame was removed if construction or planning had been incorrect. (The A85 bridge at Dalmally, Scotland suffered this fate on its first attempt, in the 1940s). The interior and lower line or curve of an arch is known as the *intrados*.

Old arches sometimes need reinforcement due to decay of the keystones, forming what is known as **bald arch**.

The gallery shows arch forms displayed in roughly the order in which they were developed.

Triangular arch
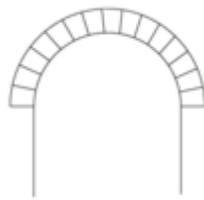
Round arch or Semi-circular arch
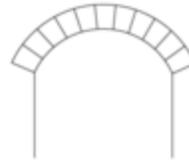
Segmental arch or arch that is less than a semicircle

Unequal round arch or Rampant round arch

Lancet arch

Equilateral pointed arch
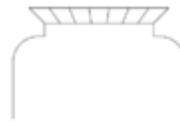
Shouldered flat arch

Three-foiled cusped arch
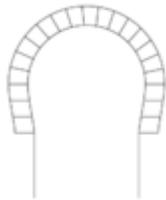
Horseshoe arch
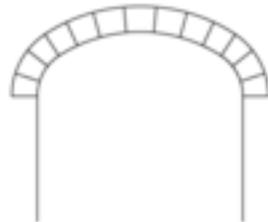
Three-centered arch
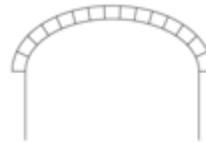
Elliptical arch

Inflexed arch

Ogee arch

Reverse ogee arch
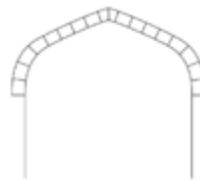
Tudor arch

Catenary or Parabolic arch

*Technical aspects*



Roman Pont-Saint-Martin

Arches in the Armenian monastery of Geghard

The arch is significant because, in theory at least, it provides a structure which eliminates tensile stresses in spanning an open space. All the forces are resolved into compressive stresses. This is useful because several of the available building materials such as stone, cast iron and concrete can strongly resist compression but are very weak when tension, shear or torsional stress is applied to them. By using the arch configuration, significant spans can be achieved. This is because all the compressive forces hold it together in a state of equilibrium. This even applies to frictionless surfaces. However, one downside is that an arch pushes outward at the base, and this needs to be restrained in some way, either with heavy sides and friction or angled cuts into bedrock or similar.

This same principle holds when the force acting on the arch is not vertical such as in spanning a doorway, but horizontal, such as in arched retaining walls or dams.

Even when using concrete, where the structure may be monolithic, the principle of the arch is used so as to benefit from the concrete's strength in resisting compressive stress. Where any other form of stress is raised, it has to be resisted by carefully placed reinforcement rods or fibres.

## *Other types*



The Delicate Arch, a natural arch in Moab, Utah

A blind arch is an arch infilled with solid construction so it cannot function as a window, door, or passageway.

A dome is an arch rotated 360 degrees about its vertical axis.

Natural rock formations may also be referred to as arches. These natural arches are formed by erosion rather than being carved or constructed by man.

A special form of the arch is the triumphal arch, usually built to celebrate a victory in war. A famous example is the Arc de Triomphe in Paris, France.

A vault is an arch extended along the axis perpendicular to the its plane; the groin vault is the intersection of two vaults.



The Gateway Arch in Saint Louis, Missouri; a sculpture based on a catenary arch



Several arches at the Casa Simón Bolívar in Havana, Cuba

**Chapter- 7**

# Other Structural Elements used in Structural Engineering

# Beam
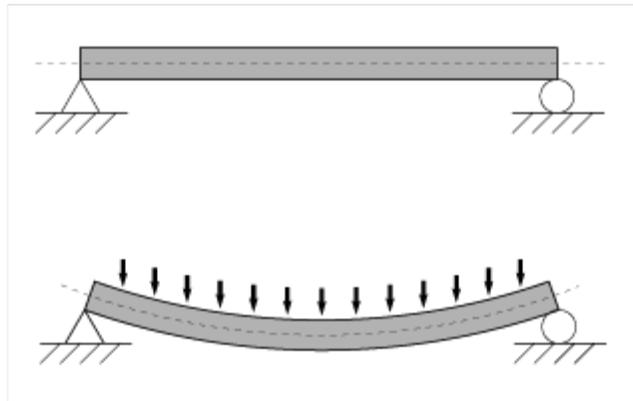


A statically determinate beam, bending under an evenly distributed load

A **beam** is a structural element that is capable of withstanding load primarily by resisting bending. The bending force induced into the material of the beam as a result of the external loads, own weight, span and external reactions to these loads is called a bending moment.

## *Overview*

Beams generally carry vertical gravitational forces but can also be used to carry horizontal loads (i.e., loads due to an earthquake or wind). The loads carried by a beam are transferred to columns, walls, or girders, which then transfer the force to adjacent structural compression members. In light frame construction the joists rest on the beam.

Beams are characterized by their profile (the shape of their cross-section), their length, and their material. In contemporary construction, beams are typically made of steel, reinforced concrete, or wood. One of the most common types of steel beam is the I-beam or wide-flange beam (also known as a "universal beam" or, for stouter sections, a "universal column"). This is commonly used in steel-frame buildings and bridges. Other

common beam profiles are the C-channel, the hollow structural section beam, the pipe, and the angle.

## *Structural characteristics*

### Moment of inertia

The moment of inertia of an object about a given axis describes how difficult it is to change its angular motion about that axis. Therefore, it encompasses not just how much mass the object has overall, but how far each bit of mass is from the axis. The farther out the object's mass is, the more rotational inertia the object has, and the more force is required to change its rotation rate.



$$Izz \cong 5^2 \cong 25 \qquad Izz \cong 15^2 \cong 225$$

Diagram of stiffness of a simple square beam (A) and universal beam (B). The universal beam flange sections are three times further apart than the solid beam's upper and lower halves. The second moment of inertia of the universal beam is nine times that of the square beam of equal cross section (universal beam web ignored for simplification)

**stress in beams**

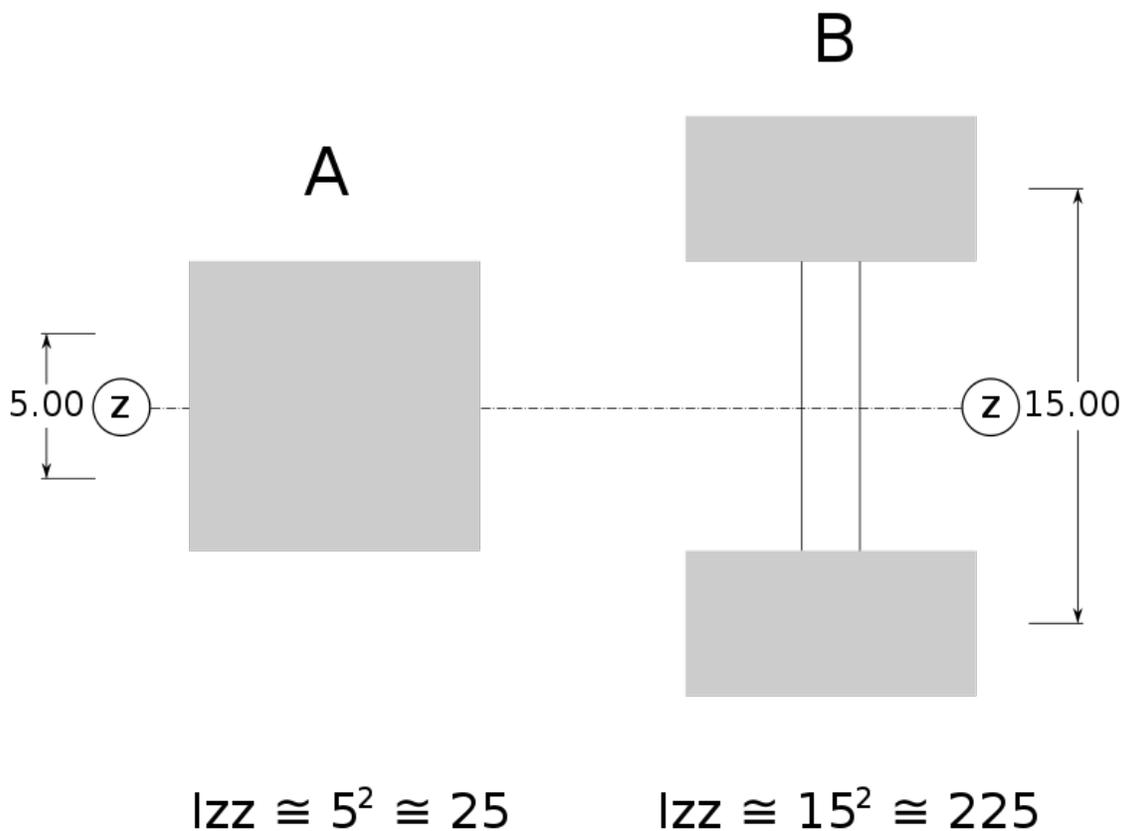Internally, beams experience compressive, tensile and shear stresses as a result of the loads applied to them. Typically, under gravity loads, the original length of the beam is slightly reduced to enclose a smaller radius arc at the top of the beam, resulting in compression, while the same original beam length at the bottom of the beam is slightly stretched to enclose a larger radius arc, and so is under tension. The same original length of the middle of the beam, generally halfway between the top and bottom, is the same as the radial arc of bending, and so it is under neither compression nor tension, and defines the neutral axis (dotted line in the beam figure). Above the supports, the beam is exposed to shear stress. There are some reinforced concrete beams in which the concrete is entirely in compression with tensile forces taken by steel tendons. These beams are known as prestressed concrete beams, and are fabricated to produce a compression more than the expected tension under loading conditions. High strength steel tendons are stretched while the beam is cast over them. Then, when the concrete has cured, the tendons are slowly released and the beam is immediately under eccentric axial loads. This eccentric loading creates an internal moment, and, in turn, increases the moment carrying capacity of the beam. They are commonly used on highway bridges.

The primary tool for structural analysis of beams is the Euler–Bernoulli beam equation. Other mathematical methods for determining the deflection of beams include "method of virtual work" and the "slope deflection method". Engineers are interested in determining deflections because the beam may be in direct contact with a brittle material such as glass. Beam deflections are also minimized for aesthetic reasons. A visibly sagging beam, even if structurally safe, is unsightly and to be avoided. A stiffer beam (high modulus of elasticity and high second moment of area) produces less deflection.

Mathematical methods for determining the beam forces (internal forces of the beam and the forces that are imposed on the beam support) include the "moment distribution method", the force or flexibility method and the direct stiffness method.

## *General shapes*

Most beams in reinforced concrete buildings have rectangular cross sections, but the most efficient cross section for a simply supported beam is an I or H section. Because of the parallel axis theorem and the fact that most of the material is away from the neutral axis, the second moment of area of the beam increases, which in turn increases the stiffness.

An I-beam is only the most efficient shape in one direction of bending: up and down looking at the profile as an I. If the beam is bent side to side, it functions as an H where it is less efficient. The most efficient shape for both directions in 2D is a box (a square shell) however the most efficient shape for bending in any direction is a cylindrical shell or tube. But, for unidirectional bending, the I or wide flange beam is superior.

Efficiency means that for the same cross sectional area (volume of beam per length) subjected to the same loading conditions, the beam deflects less.

Other shapes, like L (angles), C (channels) or tubes, are also used in construction when there are special requirements.

# Shallow Foundation

A **shallow foundation** is a type of foundation which transfers building loads to the earth very near the surface, rather than to a subsurface layer or a range of depths as does a deep foundation. Shallow foundations include **spread footing foundations**, **mat-slab foundations**, **slab-on-grade foundations**, **rubble trench foundations**, and **earthbag foundations**.

### Spread footing foundation



In ground reinforced concrete foundation in cyclonic area, Northern Australia
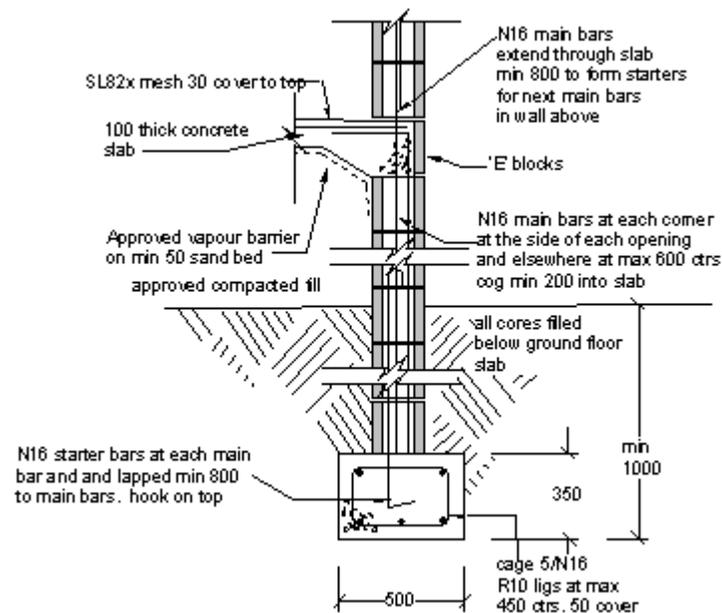
In ground reinforced concrete foundation in cyclonic area, Northern Australia

Spread footing foundations consists of strips or pads of concrete (or other materials) which transfer the loads from walls and columns to the soil or bedrock. Embedment of spread footings is controlled by several factors, including development of lateral capacity, penetration of soft near-surface layers, and penetration through near-surface layers likely to change volume due to frost heave or shrink-swell.

These foundations are common in residential construction that includes a basement, and in many commercial structures. But for high rise building it is not sufficient.

## *Mat-slab foundations*

Mat-slab foundations are used to distribute heavy column and wall loads across the entire building area, to lower the contact pressure compared to conventional spread footings. Mat-slab foundations can be constructed near the ground surface, or at the bottom of basements. In high-rise buildings, mat-slab foundations can be several meters thick, with extensive reinforcing to ensure relatively uniform load transfer.

## *Slab-on-grade foundation*



Example of slab on grade foundation

Raft slab house foundation in cyclonic area, Northern Australia
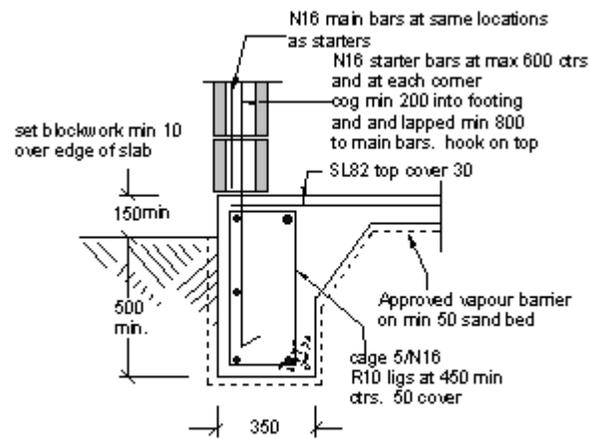


Detail 22
1: 20

Raft slab house foundation in cyclonic area, Northern Australia

Slab-on-grade foundations are a structural engineering practice whereby the concrete slab that is to serve as the foundation for the structure is formed from a mold set into the

ground. The concrete is then placed into the mold, leaving no space between the ground and the structure. This type of construction is most often seen in warmer climates, where ground freezing and thawing is less of a concern and where there is no need for heat ducting underneath the floor.

The advantages of the slab technique are that it is cheap and sturdy, and is considered less vulnerable to termite infestation because there are no hollow spaces or wood channels leading from the ground to the structure (assuming wood siding, etc., is not carried all the way to the ground on the outer walls).

The disadvantages are the lack of access from below for utility lines, the potential for large heat losses where ground temperatures fall significantly below the interior temperature, and a very low elevation that exposes the building to flood damage in even moderate rains. Remodeling or extending such a structure may also be more difficult. Over the long term, ground settling (or subsidence) may be a problem, as a slab foundation cannot be readily jacked up to compensate; proper soil compaction prior to pour can minimize this. The slab can be decoupled from ground temperatures by insulation, with the concrete poured directly over insulation (for example, Styrofoam panels), or heating provisions (such as hydronic heating) can be built into the slab (an expensive installation, with associated running expenses).

Slab-on-grade foundations are commonly used in areas with expansive clay soil, particularly in California and Texas. While elevated structural slabs actually perform better on expansive clays, it is generally accepted by the engineering community that slab-on-grade foundations offer the greatest cost-to-performance ratio for tract homes. Elevated structural slabs are generally only found on custom homes or homes with basements.

Care must be taken with the provision of services through the slab. Copper piping, commonly used to carry natural gas and water, reacts with concrete over a long period, slowly degrading until the pipe fails. Copper pipes must be *lagged* (that is, *insulated*) or run through a conduit or plumbed into the building above the slab. Electrical conduits through the slab need to be water-tight, as they extend below ground level and can potentially expose the wiring to groundwater.

### *Rubble Trench foundation*
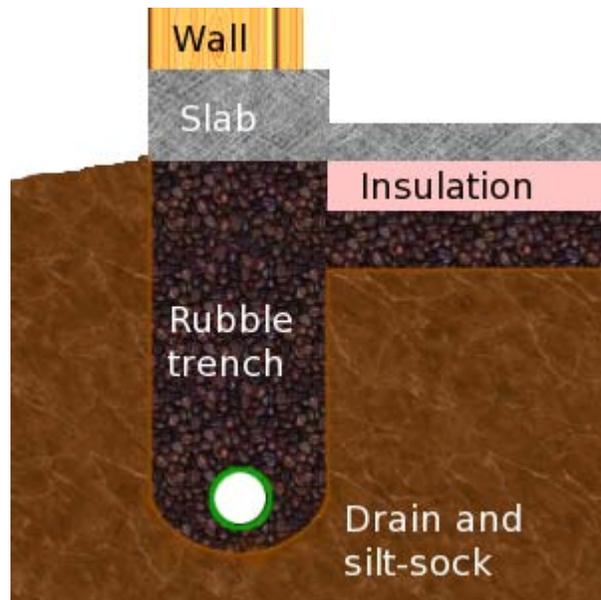


A cross section view of a rubble trench foundation

The **rubble trench foundation**, a construction approach popularized by architect Frank Lloyd Wright, is a type of foundation that uses loose stone or rubble to minimize the use of concrete and improve drainage. It is considered more environmentally friendly than other types of foundation because cement manufacturing requires the use of enormous amounts of energy. However, some soil environments (such as particularly expansive or poor load-bearing (< 1 ton/sf) soils) are not suitable for this kind of foundation.

A foundation must bear the structural loads imposed upon it and allow proper drainage of ground water to prevent expansion or weakening of soils and frost heaving. While the far more common concrete foundation requires separate measures to ensure good soil drainage, the rubble trench foundation serves both foundation functions at once.

To construct a rubble trench foundation a narrow trench is dug down below the frost line. The bottom of the trench would ideally be gently sloped to an outlet. Drainage tile, graded 1":8' to daylight, is then placed at the bottom of the trench in a bed of washed stone protected by filter fabric. The trench is then filled with either screened stone (typically 1-1/2") or recycled rubble. A steel-reinforced concrete grade beam is poured at the surface to provide ground clearance for the structure.

If an insulated slab is to be poured inside the grade beam, then the outer surface of the grade beam and the rubble trench should be insulated with rigid XPS foam board, which must be protected above grade from mechanical and UV degradation.

The rubble-trench foundation is a relatively simple, low-cost, and environmentally-friendly alternative to a conventional foundation, but may require an engineer's approval if building officials are not familiar with it. Frank Lloyd Wright used them successfully

for more than 50 years in the first half of the 20th century, and there is a revival of this style of foundation with the increased interest in green building.

### *Earthbag foundation*

The basic construction method begins by digging a trench down to undisturbed mineral subsoil. Rows of woven bags (or tubes) are filled with available material, placed into this trench, compacted with a pounder to around 1/3 thickness of pre-pounded thickness, and form a foundation. Each successive layer will have one or more strands of barbed wire placed on top. This digs into the bag's weave and prevents slippage of subsequent layers, and also resists any tendency for the outward expansion of walls. The next row of bags is offset by half a bag's width to form a staggered pattern. These are either pre-filled with material and delivered, or filled in place (often the case with Superadobe). The weight of this earth-filled bag pushes down on the barbed wire strands, locking the bag in place on the row below. The same process continues layer upon layer, forming walls. A roof can be formed by gradually sloping the walls inward to construct a dome. Traditional types of roof can also be made.

# Thin-shell Structure



Shell structure of the TWA Flight Center Building by Eero Saarinen, John F. Kennedy International Airport, New York

The Montreal Biosphère by Buckminster Fuller, 1967

Lattice Shell of the Shukhov Hyperboloid Tower. Currently under threat of demolition.

Great Court, with a lattice thin-shell roof by Buro Happold with Norman Foster, British Museum, London

**Thin-shell structures** are light weight constructions using shell elements. These elements are typically curved and are assembled to large structures. Typical applications are fuselages of aeroplanes, boat hulls and roof structures in some buildings.

A thin shell is defined as a shell with a thickness which is small compared to its other dimensions and in which deformations are not large compared to thickness. A primary difference between a shell structure and a plate structure is that, in the unstressed state, the shell structure has curvature as opposed to plates structures which are flat. Membrane action in a shell is primarily caused by in-plane forces (plane stress), though there may be secondary forces resulting from flexural deformations. Where a flat plate acts similar to a

beam with bending and shear stresses, shells are analogous to a cable which resists loads through tensile stresses. Though the ideal thin shell must be capable of developing both tension and compression.

# Chapter- 8

# Truss

In architecture and structural engineering, a **truss** is a structure comprising one or more triangular units constructed with straight members whose ends are connected at joints referred to as nodes. External forces and reactions to those forces are considered to act only at the nodes and result in forces in the members which are either tensile or compressive forces. Moments (torques) are explicitly excluded because, and only because, all the joints in a truss are treated as revolutes.

A planar truss is one where all the members and nodes lie within a two dimensional plane, while a space truss has members and nodes extending into three dimensions.



Truss bridge for a single track railway, converted to pedestrian use and pipeline support

## *Characteristics of trusses*

A truss is composed of triangles because of the structural stability of that shape and design. A triangle is the simplest geometric figure that will not change shape when the lengths of the sides are fixed. In comparison, both the angles and the lengths of a four-sided figure must be fixed for it to retain its shape.

**Planar truss**



Planar roof trusses

The simplest form of a truss is one single triangle. This type of truss is seen in a framed roof consisting of rafters and a ceiling joist. Because of the stability of this shape and the methods of analysis used to calculate the forces within it, a truss composed entirely of triangles is known as a simple truss.

A planar truss lies in a single plane. Planar trusses are typically used in parallel to form roofs and bridges.

The depth of a truss, or the height between the upper and lower chords, is what makes it an efficient structural form. A solid girder or beam of equal strength would have substantial weight and material cost as compared to a truss. For a given span length, a deeper truss will require less material in the chords and greater material in the verticals and diagonals. An optimum depth of the truss will maximize the efficiency.

**Space frame truss**

A space frame truss is a three-dimensional framework of members pinned at their ends. A tetrahedron shape is the simplest space truss, consisting of six members which meet at four joints. Large planar structures may be composed from tetrahedrons with common edges and they are also employed in the base structures of large free-standing power line pylons
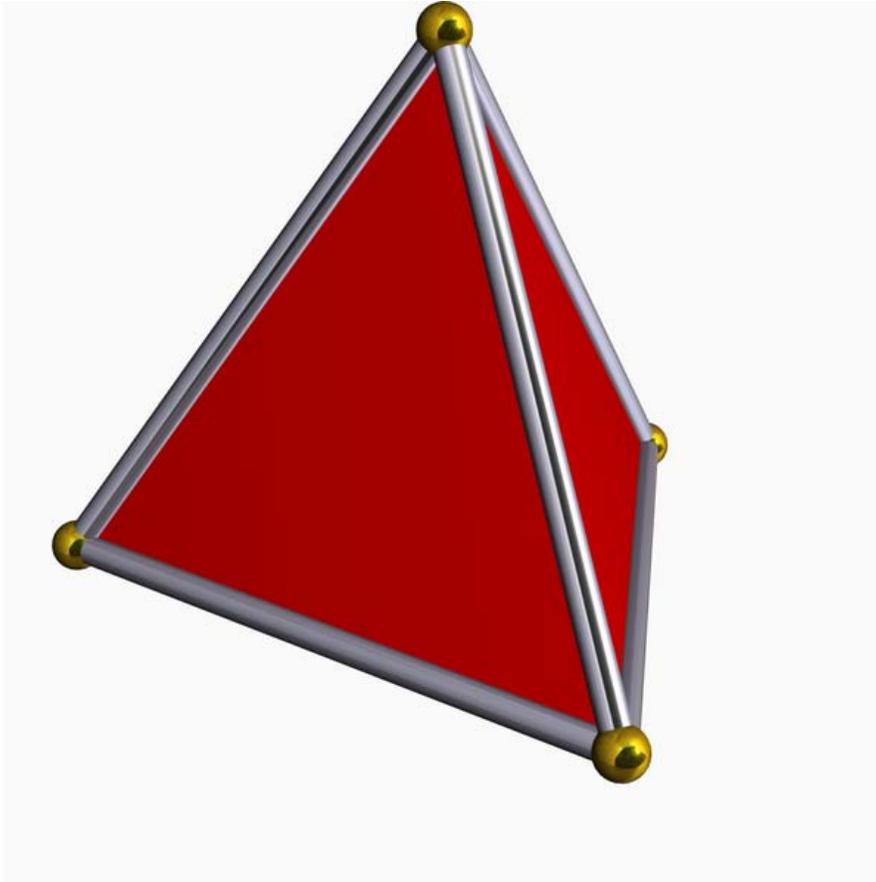
Simple tetrahedron
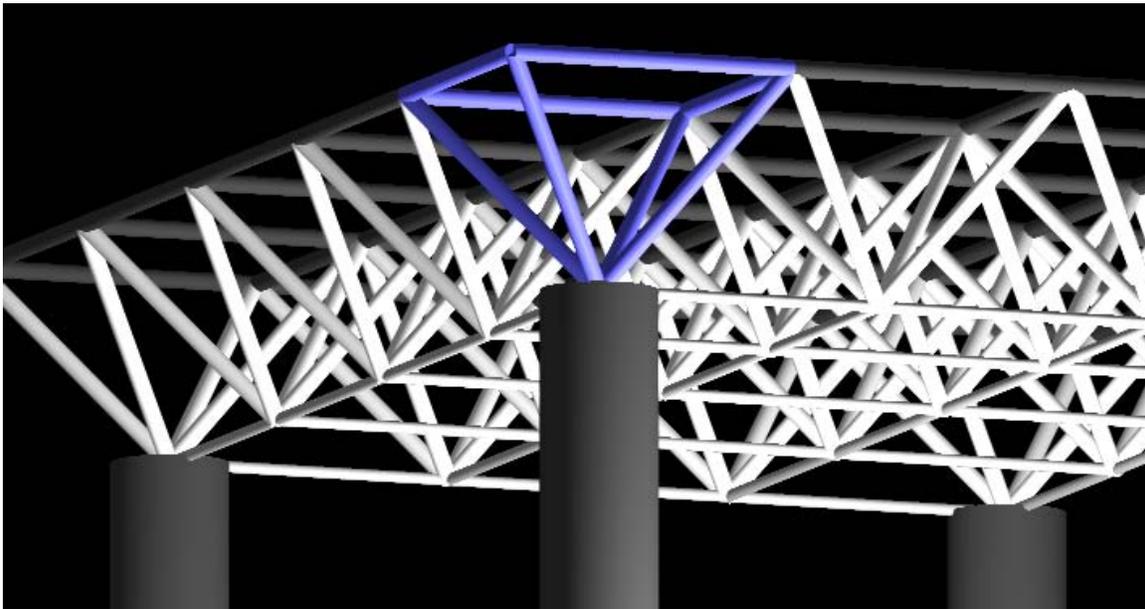


Diagram of a planar space frame such as used for a roof

Four tetrahedons form each of the two lower base structures of this power pylon

## *Truss types*



A large timber Howe truss in a commercial building

There are two basic types of truss:

- The *pitched truss*, or *common truss*, is characterized by its triangular shape. It is most often used for roof construction. Some common trusses are named according to their *web configuration*. The chord size and web configuration are determined by *span*, *load* and *spacing*.
- The *parallel chord truss*, or *flat truss*, gets its name from its parallel top and bottom chords. It is often used for floor construction.

A combination of the two is a truncated truss, used in hip roof construction. A metal plate-connected wood truss is a roof or floor truss whose wood members are connected with metal connector plates.

## Pratt truss
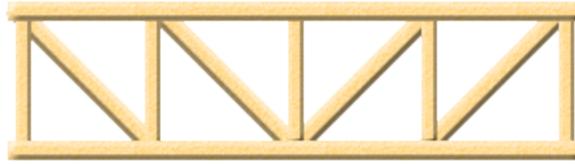
The **Pratt truss** was patented in 1844 by two Boston railway engineers, Caleb Pratt and his son Thomas Willis Pratt. The design uses vertical members for compression and horizontal members to respond to tension. What is remarkable about this style is that it remained popular even as wood gave way to iron, and even still as iron gave way to steel.. The continued popularity of the Pratt truss is probably due to the fact that the configuration of the members means that longer diagonal members are only in tension for gravity load effects. This allows these members to be used more efficiently, as slenderness effects related to buckling under compression loads (which are compounded by the length of the member) will typically not control the design. Therefore, for given planar truss with a fixed depth, the Pratt configuration is usually the most efficient under static, vertical loading.

The Southern Pacific Railroad bridge in Tempe, Arizona is a 393 meter (1,291 foot) long truss bridge built in 1912. The structure is composed of nine Pratt truss spans of varying lengths. The bridge is still in use today.

## Bowstring truss

Named for their shape, bowstring trusses were first used for arched truss bridges, known as tied-arch bridges.

Thousands of bowstring trusses were used during World War II for holding up the curved roofs of aircraft hangars and other military buildings. Many variations exist in the arrangements of the members connecting the nodes of the upper arc with those of the lower, straight sequence of members, from nearly isosceles triangles to a variant of the Platt truss.

## King post truss
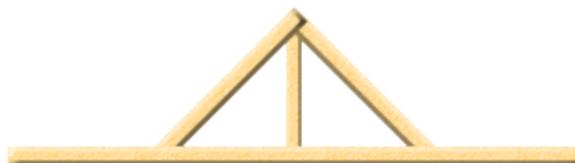
One of the simplest truss styles to implement, the **king post** consists of two angled supports leaning into a common vertical support.

The **queen post** truss, sometimes *queenpost* or *queenspost*, is similar to a king post truss in that the outer supports are angled towards the center of the structure. The primary difference is the horizontal extension at the centre which relies on beam action to provide mechanical stability. This truss style is only suitable for relatively short spans.

## Lenticular truss



The Waterville Bridge in Swatara State Park in Pennsylvania is a lenticular truss

Lenticular trusses, patented in 1878 by William Douglas, have the top and bottom chords of the truss arched, forming a lens shape. A lenticular pony truss bridge is a bridge design that involves a lenticular truss extending above and below the roadbed.

## Town's lattice truss



American architect Ithiel Town designed **Town's Lattice Truss** as an alternative to heavy-timber bridges. His design, patented in 1820 and 1835, uses easy-to-handle planks arranged diagonally with short spaces in between them.

## Vierendeel truss
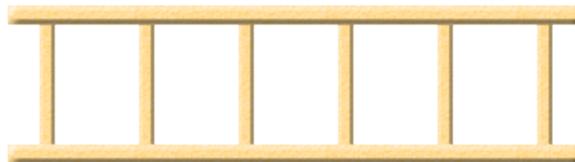




A Vierendeel bridge; note the lack of diagonal elements in the primary structure and the way bending loads are carried between elements

The **Vierendeel truss** is a truss where the members are not triangulated but form rectangular openings, and is a frame with fixed joints that are capable of transferring and resisting bending moments. Regular trusses comprise members that are commonly assumed to have pinned joints, with the implication that no moments exist at the jointed ends. This style of truss was named after the Belgian engineer Arthur Vierendeel, who developed the design in 1896. Its use for bridges is rare due to higher costs compared to a triangulated truss.

The utility of this type of truss in buildings is that a large amount of the exterior envelope remains unobstructed and can be used for fenestration and door openings. This is preferable to a braced-frame system, which would leave some areas obstructed by the diagonal braces.

## *Statics of trusses*

A truss that is assumed to comprise members that are connected by means of pin joints, and which is supported at both ends by means of hinged joints or rollers, is described as being statically determinate. Newton's Laws apply to the structure as a whole, as well as to each node or joint. In order for any node that may be subject to an external load or force to remain static in space, the following conditions must hold: the sums of all (horizontal and vertical) forces, as well as all moments acting about the node equal zero. Analysis of these conditions at each node yields the magnitude of the forces in each member of the truss. These may be compression or tension forces.

Trusses that are supported at more than two positions are said to be statically indeterminate, and the application of Newton's Laws alone is not sufficient to determine the member forces.

In order for a truss with pin-connected members to be stable, it must be entirely composed of triangles. In mathematical terms, we have the following necessary condition for stability:

$$m \geq 2j - r \qquad \text{(a)}$$

where $m$ is the total number of truss members, $j$ is the total number of joints and $r$ is the number of reactions (equal to 3 generally) in a 2-dimensional structure.

When $m = 2j - 3$, the truss is said to be *statically determinate*, because the ($m+3$) internal member forces and support reactions can then be completely determined by $2j$ equilibrium equations, once we know the external loads and the geometry of the truss. Given a certain number of joints, this is the minimum number of members, in the sense that if any member is taken out (or fails), then the truss as a whole fails. While the relation (a) is necessary, it is not sufficient for stability, which also depends on the truss geometry, support conditions and the load carrying capacity of the members.

Some structures are built with more than this minimum number of truss members. Those structures may survive even when some of the members fail. Their member forces depend on the relative stiffness of the members, in addition to the equilibrium condition described.

## *Analysis of trusses*

Cremona diagram for a plane truss

Because the forces in each of its two main girders are essentially planar, a truss is usually modelled as a two-dimensional plane frame. If there are significant out-of-plane forces, the structure must be modelled as a three-dimensional space.

The analysis of trusses often assumes that loads are applied to joints only and not at intermediate points along the members. The weight of the members is often insignificant compared to the applied loads and so is often omitted. If required, half of the weight of each member may be applied to its two end joints. Provided the members are long and slender, the moments transmitted through the joints are negligible and they can be treated as "hinges" or 'pin-joints'. Every member of the truss is then in pure compression or pure tension – shear, bending moment, and other more complex stresses are all practically zero. This makes trusses easier to analyze. This also makes trusses physically stronger than other ways of arranging material – because nearly every material can hold a much larger load in tension and compression than in shear, bending, torsion, or other kinds of force.

Structural analysis of trusses of any type can readily be carried out using a matrix method such as the direct stiffness method, the flexibility method or the finite element method.

## Forces in members

On the right is a simple, statically determinate flat truss with 9 joints and $(2 \times 9) - 3 = 15$ members. External loads are concentrated in the outer joints. Since this is a symmetrical truss with symmetrical vertical loads, it is clear to see that the reactions at A and B are equal, vertical and half the total load.

The internal forces in the members of the truss can be calculated in a variety of ways including the graphical methods:

- *Cremona diagram*
- *Culmann diagram*
- *the analytical* Ritter *method (method of sections).*

## Design of members

A truss can be thought of as a beam where the web consists of a series of separate members instead of a continuous plate. In the truss, the lower horizontal member (the **bottom chord**) and the upper horizontal member (the **top chord**) carry tension and compression, fulfilling the same function as the flanges of an I-beam. Which chord carries tension and which carries compression depends on the overall direction of bending. In the truss pictured above right, the bottom chord is in tension, and the top chord in compression.

The diagonal and vertical members form the **truss web**, and carry the shear force. Individually, they are also in tension and compression, the exact arrangement of forces is depending on the type of truss and again on the direction of bending. In the truss shown above right, the vertical members are in tension, and the diagonals are in compression.

A building under construction in Shanghai. The truss sections stabilize the building and will house mechanical floors.

In addition to carrying the static forces, the members serve additional functions of stabilizing each other, preventing buckling. In the picture to the right, the top chord is prevented from buckling by the presence of bracing and by the stiffness of the web members.

The inclusion of the elements shown is largely an engineering decision based upon economics, being a balance between the costs of raw materials, off-site fabrication, component transportation, on-site erection, the availability of machinery and the cost of labor. In other cases the appearance of the structure may take on greater importance and so influence the design decisions beyond mere matters of economics. Modern materials such as prestressed concrete and fabrication methods, such as automated welding, have significantly influenced the design of modern bridges.

Once the force on each member is known, the next step is to determine the cross section of the individual truss members. For members under tension the cross-sectional area $A$ can be found using $A = F \times \gamma / \sigma_y$, where $F$ is the force in the member, $\gamma$ is a safety factor (typically 1.5 but depending on building codes) and $\sigma_y$ is the yield tensile strength of the steel used.

The members under compression also have to be designed to be safe against buckling.

The weight of a truss member depends directly on its cross section—that weight partially determines how strong the other members of the truss need to be. Giving one member a larger cross section than on a previous iteration requires giving other members a larger cross section as well, to hold the greater weight of the first member—one needs to go through another iteration to find exactly how much greater the other members need to be. Sometimes the designer goes through several iterations of the design process to converge on the "right" cross section for each member. On the other hand, reducing the size of one member from the previous iteration merely makes the other members have a larger (and more expensive) safety factor than is technically necessary, but doesn't *require* another iteration to find a buildable truss.

The effect of the weight of the individual truss members in a large truss, such as a bridge, is usually insignificant compared to the force of the external loads.

## Design of joints

After determining the minimum cross section of the members, the last step in the design of a truss would be detailing of the bolted joints, e.g., involving shear of the bolt connections used in the joints.

## *Applications*

## Post frame structures

Component connections are critical to the structural integrity of a framing system. In buildings with large, clearspan wood trusses, the most critical connections are those between the truss and its supports. In addition to gravity-induced forces (a.k.a. bearing loads), these connections must resist shear forces acting perpendicular to the plane of the truss and uplift forces due to wind. Depending upon overall building design, the connections may also be required to transfer bending moment.

Wood posts enable the fabrication of strong, direct, yet inexpensive connections between large trusses and walls. Exact details for post-to-truss connections vary from designer to designer, and may be influenced by post type. Solid-sawn timber and glulam posts are generally notched to form a truss bearing surface. The truss is rested on the notches and bolted into place. A special plate/bracket may be added to increase connection load transfer capabilities. With mechanically-laminated posts, the truss may rest on a shortened outer-ply or on a shortened inner-ply. The later scenario places the bolts in double shear and is a very effective connection.

The HSBC Main Building, Hong Kong has an externally visible truss structure

Support structure under the Auckland Harbour Bridge

*Little Belt*: a truss bridge in Denmark

# Chapter- 9

# Civil Engineering



The Petronas Twin Towers, designed by architect Cesar Pelli and Thornton-Tomasetti and Ranhill Bersekutu Sdn Bhd engineers, were the world's tallest buildings from 1998 to 2004.

**Civil engineering** is a professional engineering discipline that deals with the design, construction, and maintenance of the physical and naturally built environment, including works like bridges, roads, canals, dams, and buildings. Civil engineering is the oldest engineering discipline after military engineering, and it was defined to distinguish non-military engineering from military engineering. It is traditionally broken into several sub-disciplines including environmental engineering, geotechnical engineering, structural engineering, transportation engineering, municipal or urban engineering, water resources engineering, materials engineering, coastal engineering, surveying, and construction engineering. Civil engineering takes place on all levels: in the public sector from municipal through to national governments, and in the private sector from individual homeowners through to international companies.

## *History of the civil engineering profession*



The Falkirk Wheel in Scotland.

Engineering has been an aspect of life since the beginnings of human existence. The earliest practices of Civil engineering may have commenced between 4000 and 2000 BC in Ancient Egypt and Mesopotamia (Ancient Iraq) when humans started to abandon a nomadic existence, thus causing a need for the construction of shelter. During this time, transportation became increasingly important leading to the development of the wheel and sailing.

Until modern times there was no clear distinction between civil engineering and architecture, and the term engineer and architect were mainly geographical variations referring to the same person, often used interchangeably. The construction of Pyramids in Egypt (circa 2700-2500 BC) might be considered the first instances of large structure constructions. Other ancient historic civil engineering constructions include the Parthenon by Iktinos in Ancient Greece (447-438 BC), the Appian Way by Roman engineers (c. 312 BC), the Great Wall of China by General Meng T'ien under orders from Ch'in Emperor Shih Huang Ti (c. 220 BC) and the stupas constructed in ancient Sri Lanka like the Jetavanaramaya and the extensive irrigation works in Anuradhapura. The Romans developed civil structures throughout their empire, including especially aqueducts, insulae, harbours, bridges, dams and roads.
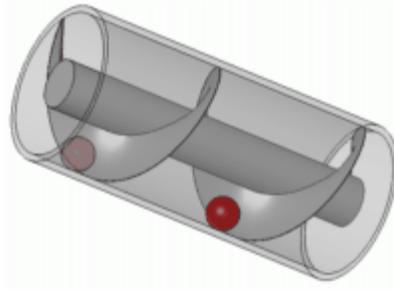


The Archimedes screw was operated by hand and could raise water efficiently.

In the 18th century, the term civil engineering was coined to incorporate all things civilian as opposed to military engineering. The first self-proclaimed civil engineer was John Smeaton who constructed the Eddystone Lighthouse. In 1771 Smeaton and some of his colleagues formed the Smeatonian Society of Civil Engineers, a group of leaders of the profession who met informally over dinner. Though there was evidence of some technical meetings, it was little more than a social society.

In 1818 the Institution of Civil Engineers was founded in London, and in 1820 the eminent engineer Thomas Telford became its first president. The institution received a Royal Charter in 1828, formally recognising civil engineering as a profession. Its charter defined civil engineering as:

the art of directing the great sources of power in nature for the use and convenience of man, as the means of production and of traffic in states, both for external and internal trade, as applied in the construction of roads, bridges, aqueducts, canals, river navigation and docks for internal intercourse and exchange, and in the construction of ports, harbours, moles, breakwaters and lighthouses, and in the art of navigation by artificial power for the purposes of commerce, and in the construction and application of machinery, and in the drainage of cities and towns.

The first private college to teach Civil Engineering in the United States was Norwich University founded in 1819 by Captain Alden Partridge. The first degree in Civil Engineering in the United States was awarded by Rensselaer Polytechnic Institute in

1835. The first such degree to be awarded to a woman was granted by Cornell University to Nora Stanton Blatch in 1905.

## *History of civil engineering*



Pont du Gard, France, a Roman aqueduct built circa 19 BC.

Civil engineering is the application of physical and scientific principles, and its history is intricately linked to advances in understanding of physics and mathematics throughout history. Because civil engineering is a wide ranging profession, including several separate specialized sub-disciplines, its history is linked to knowledge of structures, materials science, geography, geology, soils, hydrology, environment, mechanics and other fields.

Throughout ancient and medieval history most architectural design and construction was carried out by artisans, such as stone masons and carpenters, rising to the role of master builder. Knowledge was retained in guilds and seldom supplanted by advances. Structures, roads and infrastructure that existed were repetitive, and increases in scale were incremental.

One of the earliest examples of a scientific approach to physical and mathematical problems applicable to civil engineering is the work of Archimedes in the 3rd century BC, including Archimedes Principle, which underpins our understanding of buoyancy,

and practical solutions such as Archimedes' screw. Brahmagupta, an Indian mathematician, used arithmetic in the 7th century AD, based on Hindu-Arabic numerals, for excavation (volume) computations.

## *The civil engineer*

## Education and licensure



The Institution of Civil Engineers headquarters in London

Civil engineers typically possess an academic degree with a major in civil engineering. The length of study for such a degree is usually three to five years and the completed degree is usually designated as a Bachelor of Engineering, though some universities designate the degree as a Bachelor of Science. The degree generally includes units covering physics, mathematics, project management, design and specific topics in civil engineering. Initially such topics cover most, if not all, of the sub-disciplines of civil engineering. Students then choose to specialize in one or more sub-disciplines towards the end of the degree. While an Undergraduate (BEng/BSc) Degree will normally provide successful students with industry accredited qualification, some universities offer postgraduate engineering awards (MEng/MSc) which allow students to further specialize in their particular area of interest within engineering.

In most countries, a Bachelor's degree in engineering represents the first step towards professional certification and the degree program itself is certified by a professional body. After completing a certified degree program the engineer must satisfy a range of requirements (including work experience and exam requirements) before being certified. Once certified, the engineer is designated the title of Professional Engineer (in the United States, Canada and South Africa), Chartered Engineer (in most Commonwealth countries), Chartered Professional Engineer (in Australia and New Zealand), or European Engineer (in much of the European Union). There are international engineering agreements between relevant professional bodies which are designed to allow engineers to practice across international borders.

The advantages of certification vary depending upon location. For example, in the United States and Canada "only a licensed engineer may prepare, sign and seal, and submit engineering plans and drawings to a public authority for approval, or seal engineering work for public and private clients.". This requirement is enforced by state and provincial legislation such as Quebec's Engineers Act. In other countries, no such legislation exists. In Australia, state licensing of engineers is limited to the state of Queensland. Practically all certifying bodies maintain a code of ethics that they expect all members to abide by or risk expulsion. In this way, these organizations play an important role in maintaining ethical standards for the profession. Even in jurisdictions where certification has little or no legal bearing on work, engineers are subject to contract law. In cases where an engineer's work fails he or she may be subject to the tort of negligence and, in extreme cases, the charge of criminal negligence. An engineer's work must also comply with numerous other rules and regulations such as building codes and legislation pertaining to environmental law.

## Careers

There is no one typical career path for civil engineers. Most people who graduate with civil engineering degrees start with jobs that require a low level of responsibility, and as the new engineers prove their competence, they are trusted with tasks that have larger consequences and require a higher level of responsibility. However, within each branch of civil engineering career path options vary. In some fields and firms, entry-level engineers are put to work primarily monitoring construction in the field, serving as the "eyes and ears" of senior design engineers; while in other areas, entry-level engineers perform the more routine tasks of analysis or design and interpretation. Experienced engineers generally do more complex analysis or design work, or management of more complex design projects, or management of other engineers, or into specialized consulting, including forensic engineering.

### Sub-disciplines

In general, civil engineering is concerned with the overall interface of human created fixed projects with the greater world. General civil engineers work closely with surveyors and specialized civil engineers to fit and serve fixed projects within their given site, community and terrain by designing grading, drainage, pavement, water supply, sewer

service, electric and communications supply, and land divisions. General engineers spend much of their time visiting project sites, developing community consensus, and preparing construction plans. General civil engineering is also referred to as site engineering, a branch of civil engineering that primarily focuses on converting a tract of land from one usage to another. Civil engineers typically apply the principles of geotechnical engineering, structural engineering, environmental engineering, transportation engineering and construction engineering to residential, commercial, industrial and public works projects of all sizes and levels of construction.

## Coastal engineering

Coastal engineering is concerned with managing coastal areas. In some jurisdictions the terms sea defense and coastal protection are used to mean, respectively, defence against flooding and erosion. The term coastal defence is the more traditional term, but coastal management has become more popular as the field has expanded to include techniques that allow erosion to claim land.



Building construction for several apartment blocks

## Construction engineering

Construction engineering involves planning and execution of the designs from transportation, site development, hydraulic, environmental, structural and geotechnical

engineers. As construction firms tend to have higher business risk than other types of civil engineering firms, many construction engineers tend to take on a role that is more business-like in nature: drafting and reviewing contracts, evaluating logistical operations, and closely-monitoring prices of necessary supplies.

## Earthquake engineering

Earthquake engineering covers ability of various structures to withstand hazardous earthquake exposures at the sites of their particular location.



Earthquake-proof and massive pyramid El Castillo, Chichen Itza

Earthquake engineering is a sub discipline of the broader category of Structural engineering. The main objectives of earthquake engineering are:

Testing base-isolated (right) and regular (left) building model

- Understand interaction of structures with the shaky ground.

- Foresee the consequences of possible earthquakes.

- Design, construct and maintain structures to perform at earthquake exposure up to the expectations and in compliance with building codes.

# Environmental engineering



A filter bed, a part of sewage treatment

Environmental engineering deals with the treatment of chemical, biological, and/or thermal waste, the purification of water and air, and the remediation of contaminated sites, due to prior waste disposal or accidental contamination. Among the topics covered by environmental engineering are pollutant transport, water purification, waste water treatment, air pollution, solid waste treatment and hazardous waste management. Environmental engineers can be involved with pollution reduction, green engineering, and industrial ecology. Environmental engineering also deals with the gathering of information on the environmental consequences of proposed actions and the assessment of effects of proposed actions for the purpose of assisting society and policy makers in the decision making process.

Environmental engineering is the contemporary term for sanitary engineering, though sanitary engineering traditionally had not included much of the hazardous waste management and environmental remediation work covered by the term *environmental engineering*. Some other terms in use are public health engineering and environmental health engineering.

# Geotechnical engineering



Construction of an Embankment Dam in Navarra, Spain

Geotechnical engineering is an area of civil engineering concerned with the rock and soil that civil engineering systems are supported by. Knowledge from the fields of geology, material science and testing, mechanics, and hydraulics are applied by geotechnical engineers to safely and economically design foundations, retaining walls, and similar structures. Environmental concerns in relation to groundwater and waste disposal have spawned a new area of study called geoenvironmental engineering where biology and chemistry are important.

Some of the unique difficulties of geotechnical engineering are the result of the variability and properties of soil. Boundary conditions are often well defined in other

branches of civil engineering, but with soil, clearly defining these conditions can be impossible. The material properties and behavior of soil are also difficult to predict due to the variability of soil and limited investigation. This contrasts with the relatively well defined material properties of steel and concrete used in other areas of civil engineering. Soil mechanics, which describes the behavior of soil, is also complicated because soils exhibit nonlinear (stress-dependent) strength, stiffness, and dilatancy (volume change associated with application of shear stress).

## Water resources engineering



Hoover dam

Water resources engineering is concerned with the collection and management of water (as a natural resource). As a discipline it therefore combines hydrology, environmental science, meteorology, geology, conservation, and resource management. This area of civil engineering relates to the prediction and management of both the quality and the quantity of water in both underground (aquifers) and above ground (lakes, rivers, and streams) resources. Water resource engineers analyze and model very small to very large areas of the earth to predict the amount and content of water as it flows into, through, or out of a facility. Although the actual design of the facility may be left to other engineers. Hydraulic engineering is concerned with the flow and conveyance of fluids, principally water. This area of civil engineering is intimately related to the design of pipelines, water supply network, drainage facilities (including bridges, dams, channels, culverts, levees,

storm sewers), and canals. Hydraulic engineers design these facilities using the concepts of fluid pressure, fluid statics, fluid dynamics, and hydraulics, among others.

## Materials engineering

Another aspect of Civil engineering is materials science. Material engineering deals with ceramics such as concrete, mix asphalt concrete, metals Focus around increased strength, metals such as aluminum and steel, and polymers such as polymethylmethacrylate (PMMA) and carbon fibers.

Materials engineering also consists of protection and prevention like paints and finishes. Alloying is another aspect of material engineering, combining two different types of metals to produce a stronger metal.

**Structural engineering**



Burj Khalifa, the world's tallest building, in Dubai

Clifton Suspension Bridge, designed by Isambard Kingdom Brunel, in Bristol, UK

Structural engineering is concerned with the structural design and structural analysis of buildings, bridges, towers, flyovers, tunnels, off shore structures like oil and gas fields in the sea, and other structures. This involves identifying the loads which act upon a structure and the forces and stresses which arise within that structure due to those loads, and then designing the structure to successfully support and resist those loads. The loads can be self weight of the structures, other dead load, live loads, moving (wheel) load, wind load, earthquake load, load from temperature change etc. The structural engineer must design structures to be safe for their users and to successfully fulfill the function they are designed for (to be *serviceable*). Due to the nature of some loading conditions, sub-disciplines within structural engineering have emerged, including wind engineering and earthquake engineering.

Design considerations will include strength, stiffness, and stability of the structure when subjected to loads which may be static, such as furniture or self-weight, or dynamic, such as wind, seismic, crowd or vehicle loads, or transitory, such as temporary construction loads or impact. Other considerations include cost, constructability, safety, aesthetics and sustainability.

**Surveying**



US Navy Surveyor at work with a leveling instrument.

Surveying is the process by which a surveyor measures certain dimensions that generally occur on the surface of the Earth. Surveying equipment, such as levels and theodolites, are used for accurate measurement of angular deviation, horizontal, vertical and slope distances. With computerisation, electronic distance measurement (EDM), total stations, GPS surveying and laser scanning have supplemented (and to a large extent supplanted) the traditional optical instruments. This information is crucial to convert the data into a graphical representation of the Earth's surface, in the form of a map. This information is then used by civil engineers, contractors and even realtors to design from, build on, and trade, respectively. Elements of a building or structure must be correctly sized and positioned in relation to each other and to site boundaries and adjacent structures. Although surveying is a distinct profession with separate qualifications and licensing arrangements, civil engineers are trained in the basics of surveying and mapping, as well as geographic information systems. Surveyors may also lay out the routes of railways, tramway tracks, highways, roads, pipelines and streets as well as position other infrastructures, such as harbors, before construction.

**Land Surveying**

In the United States, Canada, the United Kingdom and most Commonwealth countries land surveying is considered to be a distinct profession. Land surveyors are not considered to be engineers, and have their own professional associations and licencing requirements. The services of a licenced land surveyor are generally required for boundary surveys (to establish the boundaries of a parcel using its legal description) and subdivision plans (a plot or map based on a survey of a parcel of land, with boundary

lines drawn inside the larger parcel to indicated the creation of new boundary lines and roads), both of which are generally referred to as cadastral surveying.

**Construction Surveying**

Construction surveying is generally performed by specialised technicians. Unlike land surveyors, the resulting plan does not have legal status. Construction surveyors perform the following tasks:

- Survey existing conditions of the future work site, including topography, existing buildings and infrastructure, and even including underground infrastructure whenever possible;
- Construction surveying (otherwise "lay-out" or "setting-out"): to stake out reference points and markers that will guide the construction of new structures such as roads or buildings for subsequent construction;
- Verify the location of structures during construction;
- As-Built surveying: a survey conducted at the end of the construction project to verify that the work authorized was completed to the specifications set on plans.

## Transportation engineering

Transportation engineering is concerned with moving people and goods efficiently, safely, and in a manner conducive to a vibrant community. This involves specifying, designing, constructing, and maintaining transportation infrastructure which includes streets, canals, highways, rail systems, airports, ports, and mass transit. It includes areas such as transportation design, transportation planning, traffic engineering, some aspects of urban engineering, queueing theory, pavement engineering, Intelligent Transportation System (ITS), and infrastructure management.

## Municipal or urban engineering

Municipal engineering is concerned with municipal infrastructure. This involves specifying, designing, constructing, and maintaining streets, sidewalks, water supply networks, sewers, street lighting, municipal solid waste management and disposal, storage depots for various bulk materials used for maintenance and public works (salt, sand, etc.), public parks and bicycle paths. In the case of underground utility networks, it may also include the civil portion (conduits and access chambers) of the local distribution networks of electrical and telecommunications services. It can also include the optimizing of waste collection and bus service networks. Some of these disciplines overlap with other civil engineering specialties, however municipal engineering focuses on the coordination of these infrastructure networks and services, as they are often built simultaneously, and managed by the same municipal authority.

# Chapter- 10

# Structural Health Monitoring

The process of implementing a damage detection and characterization strategy for engineering structures is referred to as **Structural Health Monitoring** (SHM). Here damage is defined as changes to the material and/or geometric properties of a structural system, including changes to the boundary conditions and system connectivity, which adversely affect the system's performance. The SHM process involves the observation of a system over time using periodically sampled dynamic response measurements from an array of sensors, the extraction of damage-sensitive features from these measurements, and the statistical analysis of these features to determine the current state of system health. For long term SHM, the output of this process is periodically updated information regarding the ability of the structure to perform its intended function in light of the inevitable aging and degradation resulting from operational environments. After extreme events, such as earthquakes or blast loading, SHM is used for rapid condition screening and aims to provide, in near real time, reliable information regarding the integrity of the structure.

## *Origins*

Qualitative and non-continuous methods have long been used to evaluate structures for their capacity to serve their intended purpose. Since the beginning of the 19th century, railroad wheel-tappers have used the sound of a hammer striking the train wheel to evaluate if damage was present. In rotating machinery, vibration monitoring has been used for decades as a performance evaluation technique. In the last ten to fifteen years, SHM technologies have emerged creating an exciting new field within various branches of engineering. Academic conferences and scientific journals have been established during this time that specifically focus on SHM. These technologies are currently becoming increasingly common.

## *Statistical Pattern Recognition Paradigm Approach*

The SHM problem can be addressed in the context of a statistical pattern recognition paradigm. This paradigm can be broken down into four parts: (1) Operational Evaluation, (2) Data Acquisition and Cleansing, (3) Feature Extraction and Data Compression, and (4) Statistical Model Development for Feature Discrimination. When one attempts to apply this paradigm to data from real world structures, it quickly becomes apparent that the ability to cleanse, compress, normalize and fuse data to account for operational and

environmental variability is a key implementation issue when addressing Parts 2-4 of this paradigm. These processes can be implemented through hardware or software and, in general, some combination of these two approaches will be used.

## Operational Evaluation

Operational evaluation attempts to answer four questions regarding the implementation of a damage identification capability:

> i) What are the life-safety and/or economic justification for performing the SHM?
> ii) How is damage defined for the system being investigated and, for multiple damage possibilities, which cases are of the most concern?
> iii) What are the conditions, both operational and environmental, under which the system to be monitored functions?
> iv) What are the limitations on acquiring data in the operational environment?

Operational evaluation begins to set the limitations on what will be monitored and how the monitoring will be accomplished. This evaluation starts to tailor the damage identification process to features that are unique to the system being monitored and tries to take advantage of unique features of the damage that is to be detected.

## Data Acquisition, Normalization and Cleansing

The data acquisition portion of the SHM process involves selecting the excitation methods, the sensor types, number and locations, and the data acquisition/storage/transmittal hardware. Again, this process will be application specific. Economic considerations will play a major role in making these decisions. The intervals at which data should be collected is another consideration that must be addressed.

Because data can be measured under varying conditions, the ability to normalize the data becomes very important to the damage identification process. As it applies to SHM, data normalization is the process of separating changes in sensor reading caused by damage from those caused by varying operational and environmental conditions. One of the most common procedures is to normalize the measured responses by the measured inputs. When environmental or operational variability is an issue, the need can arise to normalize the data in some temporal fashion to facilitate the comparison of data measured at similar times of an environmental or operational cycle. Sources of variability in the data acquisition process and with the system being monitored need to be identified and minimized to the extent possible. In general, not all sources of variability can be eliminated. Therefore, it is necessary to make the appropriate measurements such that these sources can be statistically quantified. Variability can arise from changing environmental and test conditions, changes in the data reduction process, and unit-to-unit inconsistencies.

Data cleansing is the process of selectively choosing data to pass on to or reject from the feature selection process. The data cleansing process is usually based on knowledge

gained by individuals directly involved with the data acquisition. As an example, an inspection of the test setup may reveal that a sensor was loosely mounted and, hence, based on the judgment of the individuals performing the measurement, this set of data or the data from that particular sensor may be selectively deleted from the feature selection process. Signal processing techniques such as filtering and re-sampling can also be thought of as data cleansing procedures.

Finally, the data acquisition, normalization, and cleansing portion of SHM process should not be static. Insight gained from the feature selection process and the statistical model development process will provide information regarding changes that can improve the data acquisition process.

## Feature Extraction and Data Compression

The area of the SHM process that receives the most attention in the technical literature is the identification of data features that allows one to distinguish between the undamaged and damaged structure. Inherent in this feature selection process is the condensation of the data. The best features for damage identification are, again, application specific.

One of the most common feature extraction methods is based on correlating measured system response quantities, such a vibration amplitude or frequency, with the first-hand observations of the degrading system. Another method of developing features for damage identification is to apply engineered flaws, similar to ones expected in actual operating conditions, to systems and develop an initial understanding of the parameters that are sensitive to the expected damage. The flawed system can also be used to validate that the diagnostic measurements are sensitive enough to distinguish between features identified from the undamaged and damaged system. The use of analytical tools such as experimentally-validated finite element models can be a great asset in this process. In many cases the analytical tools are used to perform numerical experiments where the flaws are introduced through computer simulation. Damage accumulation testing, during which significant structural components of the system under study are degraded by subjecting them to realistic loading conditions, can also be used to identify appropriate features. This process may involve induced-damage testing, fatigue testing, corrosion growth, or temperature cycling to accumulate certain types of damage in an accelerated fashion. Insight into the appropriate features can be gained from several types of analytical and experimental studies as described above and is usually the result of information obtained from some combination of these studies.

The operational implementation and diagnostic measurement technologies needed to perform SHM produce more data than traditional uses of structural dynamics information. A condensation of the data is advantageous and necessary when comparisons of many feature sets obtained over the lifetime of the structure are envisioned. Also, because data will be acquired from a structure over an extended period of time and in an operational environment, robust data reduction techniques must be developed to retain feature sensitivity to the structural changes of interest in the presence of environmental and operational variability. To further aid in the extraction and

recording of quality data needed to perform SHM, the statistical significance of the features should be characterized and used in the condensation process.

## Statistical Model Development

The portion of the SHM process that has received the least attention in the technical literature is the development of statistical models for discrimination between features from the undamaged and damaged structures. Statistical model development is concerned with the implementation of the algorithms that operate on the extracted features to quantify the damage state of the structure. The algorithms used in statistical model development usually fall into three categories. When data are available from both the undamaged and damaged structure, the statistical pattern recognition algorithms fall into the general classification referred to as supervised learning. Group classification and regression analysis are categories of supervised learning algorithms. Unsupervised learning refers to algorithms that are applied to data not containing examples from the damaged structure. Outlier or novelty detection is the primary class of algorithms applied in unsupervised learning applications. All of the algorithms analyze statistical distributions of the measured or derived features to enhance the damage identification process.

## *The Fundamental Axioms of SHM*

Based on the extensive literature that has developed on SHM over the last 20 years, it can be argued that this field has matured to the point where several fundamental axioms, or general principles, have emerged. The axioms are listed as follows:

- Axiom I: All materials have inherent flaws or defects;
- Axiom II: The assessment of damage requires a comparison between two system states;
- Axiom III: Identifying the existence and location of damage can be done in an unsupervised learning mode, but identifying the type of damage present and the damage severity can generally only be done in a supervised learning mode;
- Axiom IVa: Sensors cannot measure damage. Feature extraction through signal processing and statistical classification is necessary to convert sensor data into damage information;
- Axiom IVb: Without intelligent feature extraction, the more sensitive a measurement is to damage, the more sensitive it is to changing operational and environmental conditions;
- Axiom V: The length- and time-scales associated with damage initiation and evolution dictate the required properties of the SHM sensing system;
- Axiom VI: There is a trade-off between the sensitivity to damage of an algorithm and its noise rejection capability;
- Axiom VII: The size of damage that can be detected from changes in system dynamics is inversely proportional to the frequency range of excitation.

## *SHM Components*

SHM System's elements include:

- Structure
- Sensors
- Data acquisition systems
- Data transfer and storage mechanism
- Data management
- Data interpretation and diagnosis:

  1) System Identification
  2) Structural model update
  3) Structural condition assessment
  4) Prediction of remaining service life

An example of this technology is embedding sensors in structures like bridges and aircraft. These sensors provide real time monitoring of various structural changes like stress and strain. In the case of civil engineering structures, the data provided by the sensors is usually transmitted to a remote data acquisition centres. With the aid of modern technology, real time control of structures (Active Structural Control) based on the information of sensors is possible

## *Examples*

### Wind and Structural Health Monitoring System for Bridges in Hong Kong

The **Wind and Structural Health Monitoring System** (WASHMS) is a sophisticated bridge monitoring system, costing US$1.3 million, used by the Hong Kong Highways Department to ensure road user comfort and safety of the Tsing Ma, Ting Kau, and Kap Shui Mun bridges that run between Hong Kong and the Hong Kong Airport.

In order to oversee the integrity, durability and reliability of the bridges, WASHMS has four different levels of operation: sensory systems, data acquisition systems, local centralised computer systems and global central computer system.

The sensory system consists of approximately 900 sensors and their relevant interfacing units. With more than 350 sensors on the Tsing Ma bridge, 350 on Ting Kau and 200 on Kap Shui Mun, the structural behaviour of the bridges is measured 24 hours a day, seven days a week.

The sensors include accelerometers, strain gauges, displacement transducers, level sensing stations, anemometers, temperature sensors and dynamic weight-in-motion sensors. They measure everything from tarmac temperature and strains in structural

members to wind speed and the deflection and rotation of the kilometres of cables and any movement of the bridge decks and towers.

These sensors are the early warning system for the bridges, providing the essential information that help the Highways Department to accurately monitor the general health conditions of the bridges.

The structures have been built to withstand up to a one-minute mean wind speed of 95 metres per second. In 1997, when Hong Kong had a direct hit from Typhoon Victor, wind speeds of 110 to 120 kilometres per hour were recorded. However, the highest wind speed on record occurred during Typhoon Wanda in 1962 when a 3 second gust wind speed was recorded at 78.8 metres per second, 284 kilometres per hour.

The information from these hundreds of different sensors is transmitted to the data acquisition outstation units. There are three data acquisition outstation units on Tsing Ma bridge, three on Ting Kau and two on the Kap Shui Mun.

The computing powerhouse for these systems is in the administrative building used by the Highways Department in Tsing Yi. The local central computer system provides data collection control, post-processing, transmission and storage. The global system is used for data acquisition and analysis, assessing the physical conditions and structural functions of the bridges and for integration and manipulation of the data acquisition, analysis and assessing processes.

- o   Monitoring Hong Kong's Bridges Real-Time Kinematic Spans The Gap

## Other large examples

The following project are currently known as some of the biggest on-going bridge monitoring

- The Rio–Antirrio bridge, Greece: has more than 100 sensors monitoring the structure and the traffic in real time.
- Millau Viaduc, France: has one of the largest systems with fiber optics in the world which is considered state of the art.
- The Huey P Long bridge, USA: has over 800 static and dynamic strain gauges designed to measure axial and bending load effects.
- The Fatih Sultan Mehmet Bridge, Turkey: also known as the Second Bosphorus Bridge. It has been monitored using an innovative wireless sensor network with normal traffic condition.

## *Structural Health Monitoring for bridges*

Health monitoring of large bridges shall be performed by simultaneous measurement of loads on the bridge and effects of these loads. It typically includes monitoring of:

- Wind and weather
- Traffic
- Prestressing and stay cables
- Deck
- Pylons
- Ground

Provided with this knowledge, the engineer can:

- Estimate the loads and their effects
- Estimate the state of fatigue
- Forecast the probable evolution of the bridge

References are available that provide an introduction to the application of fiber optic sensors to Structural Health Monitoring on bridges.

# Chapter- 11

# Telemetry

**Telemetry** is a technology that allows remote measurement and reporting of information. The word is derived from Greek roots *tele* = remote, and *metron* = measure. Systems that need external instructions and data to operate require the counterpart of telemetry, telecommand.

Although the term commonly refers to wireless data transfer mechanisms (e.g. using radio or infrared systems), it also encompasses data transferred over other media, such as a telephone or computer network, optical link or other wired communications. Many modern telemetry systems take advantage of the low cost and ubiquity of GSM networks by using SMS to receive and transmit telemetry data.

## *History*

Telemetering information over wire had its origins in the 19th century. One of the first data transmission circuits was developed in 1845 between the Russian Tsar's Winter Palace and the army's headquarters. In 1874, French engineers built a system of weather and snow-depth sensors on Mont Blanc that transmitted real-time information to Paris. In 1901 the American inventor C. Michalke patented the selsyn, a circuit for sending synchronized rotation information over distances. In 1906, a set of seismic stations were built with telemetering to the Pulkovo Observatory in Russia. In 1912, Commonwealth Edison developed a system of telemetry to monitor electrical loads on its power grid. The Panama Canal (completed 1913-1914) used extensive telemetry systems to monitor locks and water levels.

Wireless telemetry made early appearances in the radiosonde developed concurrently in 1930 by Robert Bureau in France and Pavel Molchanov in Russia. Mochanov's system modulated temperature and pressure measurements by converting them into wireless Morse code. The German V-2 rocket used a system of primitive multiplexed radio signals called "Messina" to report 4 rocket parameters, but it was so unreliable that Von Braun once claimed it was more useful to watch the rocket through binoculars. In both the USA and USSR, the Messina system was quickly replaced with better systems, in both cases based on pulse-position modulation.

Early Soviet missile and space telemetry systems developed in the late 1940s used either pulse-position modulation (e.g., the Tral telemetry system developed by OKB-MEI) or

pulse-duration modulation (e.g., the RTS-5 system developed by NII-885). In the USA, early work employed similar systems, but were later replaced by pulse-code modulation (PCM), for example in the Mars probe Mariner 4. Later Soviet interplanetary probes used redundant radio systems, transmitting telemetry by PCM on a decimeter band and PPM on a centimeter band.

## *Applications*

### Motor racing

Telemetry is a key factor in modern motor racing, allowing race engineers to interpret the vast amount of data collected during a test or race, and use that to properly tune the car for optimum performance. Systems used in some series, namely Formula One, have become advanced to the point where the potential lap time of the car can be calculated and this is what the driver is expected to meet. Some examples of useful measurements on a race car include accelerations (G forces) in 3 axis, temperature readings, wheel speed, and the displacement of the suspension. In Formula 1, the driver inputs are also recorded so that the team can assess driver performance and, in the case of an accident, the FIA can determine or rule out driver error as a possible cause.

Later developments saw two way telemetry, that allowed the engineers the ability to update calibrations on the car in real time, possibly while it is out on the track. In Formula 1, two-way telemetry surfaced in the early nineties from TAG electronics, and consisted of a message display on the dashboard which the team could update. Its development continued until May 2001, at which point it was first allowed on the cars. By 2002 the teams were able to change engine mapping and deactivate particular engine sensors from the pits while the car was on track. For the 2003 season, the FIA banned two-way telemetry from Formula 1, however the technology still exists and could eventually find its way into other forms of racing or road cars.

In addition to that telemetry has also been applied to the use of Yacht racing. The technology was applied to the Oracle's USA-76.

### Agriculture

Most activities related to healthy crops and good yields depend on timely availability of weather and soil data. Therefore, wireless weather stations play a major role in disease prevention and precision irrigation. These stations transmit major parameters needed for good decisions to a base station: air temperature and relative humidity, precipitation and leaf wetness (for disease prediction models), solar radiation and wind speed (to calculate evapotranspiration), water deficit stress (WDS) leaf sensors and soil moisture, crucial to understand the progress of water into soil and roots for irrigation decisions.

Because local micro-climates can vary significantly, such data needs to come from right within the crop. Monitoring stations usually transmit data back by terrestrial radio though

occasionally satellite systems are used. Solar power is often employed to make the station independent from local infrastructure.

## Water management

Telemetry has become indispensable for water management applications, including water quality and stream gauging functions. Major applications include AMR (automatic meter reading), groundwater monitoring, leak detection in distribution pipelines and equipment surveillance. Having data available in almost real time allows quick reactions to occurrences in the field.

## Defense, space and resource exploration systems

Telemetry is an enabling technology for large complex systems such as missiles, RPVs, spacecraft, oil rigs and chemical plants because it allows automatic monitoring, alerting, and record-keeping necessary for safe, efficient operations. Space agencies such as NASA, ESA, and other agencies use telemetry/telecommand systems to collect data from operating spacecraft and satellites.

Telemetry is vital in the development phase of missiles, satellites and aircraft because the system might be destroyed after/during the test. Engineers need critical system parameters to analyze (and improve) the performance of the system. Without telemetry, these data would often be unavailable.

## Rocketry

In rocketry, telemetry equipment forms an integral part of the rocket range assets used to monitor the progress of a rocket launch. Some special problems are the extreme environment (temperature, accelerations, vibrations...), the energy supply, the precise alignment of the antenna and (at long distances, e.g. in spaceflight) the signal travel time.

## Flight test

Flight test programs typically telemeter data collected from on-board flight test instrumentation over a PCM/RF link. This data is analyzed in real-time for safety reasons and to provide feedback to the test pilot. Particular challenges for telemetering this data includes fading, multipath propagation and the Doppler effect. The bandwidth of the telemetry link is often insufficient to transfer all the data acquired and therefore only a limited set is sent to the ground for real-time processing while an on-board recorder ensures the full dataset is available for post flight analysis.

## Enemy intelligence

Telemetry was a vital source of intelligence for the US and UK when Soviet missiles were tested. For this purpose, the US operated a listening post in Iran. Eventually, the Russians discovered this kind of US intelligence gathering and encrypted their telemetry

signals of missile tests. Telemetry was a vital source for the Soviets who would operate listening ships in Cardigan Bay to eavesdrop on the UK missile tests carried out there.

## Energy monitoring

In factories, buildings, and houses, energy consumption of systems such as HVAC are monitored at multiple locations, together with the related parameters (e.g. temperature) via wireless telemetry to one central location. The information is collected and processed enabling intelligent decisions regarding the most efficient use of energy to be implemented. Such systems also facilitate predictive maintenance.

## Resource distribution

Many resources need to be distributed over wide areas. Telemetry is essential in these cases, since it allows the system to channel resources to where they are needed.

## Medicine

Telemetry also is used for patients (biotelemetry) who are at risk of abnormal heart activity, generally in a coronary care unit. Such patients are outfitted with measuring, recording and transmitting devices. A data log can be useful in diagnosis of the patient's condition by doctors. An alerting function can alert nurses if the patient is suffering from an acute or dangerous condition.

Also a system that is available in medical-surgical nursing to monitor a condition where heart condition may be ruled out. Or to monitor a response to antiarrhythmic medications such as Digoxin.

**Fisheries and wildlife research and management**



Common Seal with a transceiver on his back

Telemetry is now being used to study wildlife, and has been particularly useful for monitoring threatened species at the individual level. Animals under study may be fitted with instrumentation ranging from simple tags to cameras, GPS packages and transceivers to provide position and other basic information to scientists and stewards.

Telemetry is used in hydroacoustic assessments for fish which have traditionally employed mobile surveys from boats to evaluate fish biomass and spatial distributions. Conversely, fixed-location techniques use stationary transducers to monitor passing fish. While the first serious attempts to quantify fish biomass were conducted in the 1960s, major advances in equipment and techniques took place at hydropower dams in the 1980s. Some evaluations monitored fish passage 24 hours a day for over a year, producing estimates of fish entrainment rates, fish sizes, and spatial and temporal distributions.

In the 1970s, the dual-beam technique was invented, permitting direct estimation of fish size in-situ via its target strength. The first portable split-beam hydroacoustic system was developed by HTI in 1991, and provided more accurate and less variable estimates of fish target strength than the dual-beam method. It also permitted tracking of fish in 3D, giving each fish's swimming path and absolute direction of movement. This feature proved important for evaluations of entrained fish in water diversions as well as for studies of migratory fish in rivers. In the last 35 years, tens of thousands of mobile and fixed-location hydroacoustic evaluations have been conducted worldwide.

## Retail businesses

At a 2005 workshop in Las Vegas, a seminar noted the introduction of telemetry equipment that would allow vending machines to communicate sales and inventory data to a route truck or to a headquarters. This data could be used for a variety of purposes, such as eliminating the need for the driver to make a first trip to see what items need to be restocked before bringing the inventory inside.

Retailers are also beginning to make use of RFID tags to track inventory and prevent shoplifting. Most of these tags passively respond to RFID readers (e.g. at the cashier), but active RFID tags are available that periodically transmit telemetry to a base station.

## Law enforcement

Telemetry hardware is useful for tracking persons and property in law enforcement. An ankle collar worn by convicts on probation can warn authorities if a person violates the terms of his or her parole, such as by straying from authorized boundaries or visiting an unauthorized location. Telemetry equipment has also given rise to the concept of bait cars, where law enforcement can rig a car with cameras and tracking equipment and leave it somewhere they expect it to be stolen. When stolen, the telemetry equipment reports the location of the vehicle, and gives law enforcement the ability to deactivate the engine and lock the doors once it is stopped by responding officers.

## Electrical energy providers

In some countries telemetry is used to assess the amount of electrical energy users have consumed. The electricity meter communicates with a concentrator and the latter sends that information through GPRS or GSM to the electrical energy provider's server.

## *International standards*

As in other telecommunications fields, international standards exist for telemetry equipment and software. CCSDS and IRIG are such standards.

# Remote Sensing

Synthetic aperture radar image of Death Valley colored using polarimetry.

**Remote sensing** is the small- or large-scale acquisition of information of an object or phenomenon, by the use of either recording or real-time sensing device(s) that are wireless, or not in physical or intimate contact with the object (such as by way of aircraft, spacecraft, satellite, buoy, or ship). In practice, remote sensing is the stand-off collection through the use of a variety of devices for gathering information on a given object or area. Thus, Earth observation or weather satellite collection platforms, ocean and atmospheric observing weather buoy platforms, the monitoring of a parolee via an ultrasound identification system, Magnetic Resonance Imaging (MRI), Positron Emission Tomography (PET), X-radiation (X-RAY) and space probes are all examples of remote sensing. In modern usage, the term generally refers to the use of imaging sensor technologies including: instruments found in aircraft and spacecraft as well as those used in electrophysiology, and is distinct from other imaging-related fields such as medical imaging.

## *Overview*

There are two main types of remote sensing: passive remote sensing and active remote sensing. Passive sensors detect natural radiation that is emitted or reflected by the object or surrounding area being observed. Reflected sunlight is the most common source of radiation measured by passive sensors. Examples of passive remote sensors include film photography, infrared, charge-coupled devices, and radiometers. Active collection, on the other hand, emits energy in order to scan objects and areas whereupon a sensor then detects and measures the radiation that is reflected or backscattered from the target. RADAR is an example of active remote sensing where the time delay between emission and return is measured, establishing the location, height, speed and direction of an object.

Remote sensing makes it possible to collect data on dangerous or inaccessible areas. Remote sensing applications include monitoring deforestation in areas such as the Amazon Basin, glacial features in Arctic and Antarctic regions, and depth sounding of coastal and ocean depths. Military collection during the cold war made use of stand-off collection of data about dangerous border areas. Remote sensing also replaces costly and slow data collection on the ground, ensuring in the process that areas or objects are not disturbed.

Orbital platforms collect and transmit data from different parts of the electromagnetic spectrum, which in conjunction with larger scale aerial or ground-based sensing and analysis, provides researchers with enough information to monitor trends such as El Niño and other natural long and short term phenomena. Other uses include different areas of the earth sciences such as natural resource management, agricultural fields such as land usage and conservation, and national security and overhead, ground-based and stand-off collection on border areas.

By satellite, aircraft, spacecraft, buoy, ship, and helicopter images, data is created to analyze and compare things like vegetation rates, erosion, pollution, forestry, weather, and land use. These things can be mapped, imaged, tracked and observed. The process of

remote sensing is also helpful for city planning, archaeological investigations, military observation and geomorphological surveying.

## *Data acquisition techniques*

The basis for multispectral collection and analysis is that of examined areas or objects that reflect or emit radiation that stand out from surrounding areas.

### Applications of remote sensing data

- Conventional radar is mostly associated with aerial traffic control, early warning, and certain large scale meteorological data. Doppler radar is used by local law enforcements' monitoring of speed limits and in enhanced meteorological collection such as wind speed and direction within weather systems. Other types of active collection includes plasmas in the ionosphere. Interferometric synthetic aperture radar is used to produce precise digital elevation models of large scale terrain.
- Laser and radar altimeters on satellites have provided a wide range of data. By measuring the bulges of water caused by gravity, they map features on the seafloor to a resolution of a mile or so. By measuring the height and wave-length of ocean waves, the altimeters measure wind speeds and direction, and surface ocean currents and directions.
- Light detection and ranging (LIDAR) is well known in examples of weapon ranging, laser illuminated homing of projectiles. LIDAR is used to detect and measure the concentration of various chemicals in the atmosphere, while airborne LIDAR can be used to measure heights of objects and features on the ground more accurately than with radar technology. Vegetation remote sensing is a principal application of LIDAR.
- Radiometers and photometers are the most common instrument in use, collecting reflected and emitted radiation in a wide range of frequencies. The most common are visible and infrared sensors, followed by microwave, gamma ray and rarely, ultraviolet. They may also be used to detect the emission spectra of various chemicals, providing data on chemical concentrations in the atmosphere.
- Stereographic pairs of aerial photographs have often been used to make topographic maps by imagery and terrain analysts in trafficability and highway departments for potential routes.
- Simultaneous multi-spectral platforms such as Landsat have been in use since the 70's. These thematic mappers take images in multiple wavelengths of electro-magnetic radiation (multi-spectral) and are usually found on Earth observation satellites, including (for example) the Landsat program or the IKONOS satellite. Maps of land cover and land use from thematic mapping can be used to prospect for minerals, detect or monitor land usage, deforestation, and examine the health of indigenous plants and crops, including entire farming regions or forests.
- Within the scope of the combat against desertification, remote sensing allows to follow-up and monitor risk areas in the long term, to determine desertification

factors, to support decision-makers in defining relevant measures of environmental management, and to assess their impacts.

## Geodetic

- Overhead geodetic collection was first used in aerial submarine detection and gravitational data used in military maps. This data revealed minute perturbations in the Earth's gravitational field (geodesy) that may be used to determine changes in the mass distribution of the Earth, which in turn may be used for geological studies.

## Acoustic and near-acoustic

- Sonar: *passive sonar*, listening for the sound made by another object (a vessel, a whale etc); *active sonar*, emitting pulses of sounds and listening for echoes, used for detecting, ranging and measurements of underwater objects and terrain.
- Seismograms taken at different locations can locate and measure earthquakes (after they occur) by comparing the relative intensity and precise timing.

To coordinate a series of large-scale observations, most sensing systems depend on the following: platform location, what time it is, and the rotation and orientation of the sensor. High-end instruments now often use positional information from satellite navigation systems. The rotation and orientation is often provided within a degree or two with electronic compasses. Compasses can measure not just azimuth (i. e. degrees to magnetic north), but also altitude (degrees above the horizon), since the magnetic field curves into the Earth at different angles at different latitudes. More exact orientations require gyroscopic-aided orientation, periodically realigned by different methods including navigation from stars or known benchmarks.

Resolution impacts collection and is best explained with the following relationship: less resolution=less detail & larger coverage, More resolution=more detail, less coverage. The skilled management of collection results in cost-effective collection and avoid situations such as the use of multiple high resolution data which tends to clog transmission and storage infrastructure.

## *Data processing*

Generally speaking, remote sensing works on the principle of the *inverse problem*. While the object or phenomenon of interest (the **state**) may not be directly measured, there exists some other variable that can be detected and measured (the **observation**), which may be related to the object of interest through the use of a data-derived computer model. The common analogy given to describe this is trying to determine the type of animal from its footprints. For example, while it is impossible to directly measure temperatures in the upper atmosphere, it is possible to measure the spectral emissions from a known chemical species (such as carbon dioxide) in that region. The frequency of the emission

may then be related to the temperature in that region via various thermodynamic relations.

The quality of remote sensing data consists of its spatial, spectral, radiometric and temporal resolutions.

Spatial resolution
> The size of a pixel that is recorded in a raster image – typically pixels may correspond to square areas ranging in side length from 1 to 1,000 metres (3.3 to 3,300 ft).

Spectral resolution
> The wavelength width of the different frequency bands recorded – usually, this is related to the number of frequency bands recorded by the platform. Current Landsat collection is that of seven bands, including several in the infra-red spectrum, ranging from a spectral resolution of 0.07 to 2.1 μm. The Hyperion sensor on Earth Observing-1 resolves 220 bands from 0.4 to 2.5 μm, with a spectral resolution of 0.10 to 0.11 μm per band.

Radiometric resolution
> The number of different intensities of radiation the sensor is able to distinguish. Typically, this ranges from 8 to 14 bits, corresponding to 256 levels of the gray scale and up to 16,384 intensities or "shades" of colour, in each band. It also depends on the instrument noise.

Temporal resolution
> The frequency of flyovers by the satellite or plane, and is only relevant in time-series studies or those requiring an averaged or mosaic image as in deforesting monitoring. This was first used by the intelligence community where repeated coverage revealed changes in infrastructure, the deployment of units or the modification/introduction of equipment. Cloud cover over a given area or object makes it necessary to repeat the collection of said location.

In order to create sensor-based maps, most remote sensing systems expect to extrapolate sensor data in relation to a reference point including distances between known points on the ground. This depends on the type of sensor used. For example, in conventional photographs, distances are accurate in the center of the image, with the distortion of measurements increasing the farther you get from the center. Another factor is that of the platen against which the film is pressed can cause severe errors when photographs are used to measure ground distances. The step in which this problem is resolved is called georeferencing, and involves computer-aided matching up of points in the image (typically 30 or more points per image) which is extrapolated with the use of an established benchmark, "warping" the image to produce accurate spatial data. As of the early 1990s, most satellite images are sold fully georeferenced.

In addition, images may need to be radiometrically and atmospherically corrected.

Radiometric correction

gives a scale to the pixel values, e. g. the monochromatic scale of 0 to 255 will be converted to actual radiance values.

Atmospheric correction
> eliminates atmospheric haze by rescaling each frequency band so that its minimum value (usually realised in water bodies) corresponds to a pixel value of 0. The digitizing of data also make possible to manipulate the data by changing gray-scale values.

Interpretation is the critical process of making sense of the data. The first application was that of aerial photographic collection which used the following process; spatial measurement through the use of a light table in both conventional single or stereographic coverage, added skills such as the use of photogrammetry, the use of photomosaics, repeat coverage, Making use of objects' known dimensions in order to detect modifications. Image Analysis is the recently developed automated computer-aided application which is in increasing use.

Object-Based Image Analysis (OBIA) is a sub-discipline of GIScience devoted to partitioning remote sensing (RS) imagery into meaningful image-objects, and assessing their characteristics through spatial, spectral and temporal scale.

Old data from remote sensing is often valuable because it may provide the only long-term data for a large extent of geography. At the same time, the data is often complex to interpret, and bulky to store. Modern systems tend to store the data digitally, often with lossless compression. The difficulty with this approach is that the data is fragile, the format may be archaic, and the data may be easy to falsify. One of the best systems for archiving data series is as computer-generated machine-readable ultrafiche, usually in typefonts such as OCR-B, or as digitized half-tone images. Ultrafiches survive well in standard libraries, with lifetimes of several centuries. They can be created, copied, filed and retrieved by automated systems. They are about as compact as archival magnetic media, and yet can be read by human beings with minimal, standardized equipment.

## Data processing levels

To facilitate the discussion of data processing in practice, several processing "levels" were first defined in 1986 by NASA as part of its Earth Observing System and steadily adopted since then, both internally at NASA (e. g., ) and elsewhere (e. g., ); these definitions are:

| Level | Description |
|---|---|
| 0 | Reconstructed, unprocessed instrument and payload data at full resolution, with any and all communications artifacts (e. g., synchronization frames, communications headers, duplicate data) removed. |
| 1a | Reconstructed, unprocessed instrument data at full resolution, time-referenced, and annotated with ancillary information, including radiometric and geometric calibration coefficients and georeferencing parameters (e. g., platform ephemeris) |

|  | computed and appended but not applied to the Level 0 data (or if applied, in a manner that level 0 is fully recoverable from level 1a data). |
|---|---|
| 1b | Level 1a data that have been processed to sensor units (e. g., radar backscatter cross section, brightness temperature, etc.); not all instruments have Level 1b data; level 0 data is not recoverable from level 1b data. |
| 2 | Derived geophysical variables (e. g., ocean wave height, soil moisture, ice concentration) at the same resolution and location as Level 1 source data. |
| 3 | Variables mapped on uniform spacetime grid scales, usually with some completeness and consistency (e. g., missing points interpolated, complete regions mosaicked together from multiple orbits, etc). |
| 4 | Model output or results from analyses of lower level data (i. e., variables that were not measured by the instruments but instead are derived from these measurements). |

A Level 1 data record is the most fundamental (i. e., highest reversible level) data record that has significant scientific utility, and is the foundation upon which all subsequent data sets are produced. Level 2 is the first level that is directly usable for most scientific applications; its value is much greater than the lower levels. Level 2 data sets tend to be less voluminous than Level 1 data because they have been reduced temporally, spatially, or spectrally. Level 3 data sets are generally smaller than lower level data sets and thus can be dealt with without incurring a great deal of data handling overhead. These data tend to be generally more useful for many applications. The regular spatial and temporal organization of Level 3 datasets makes it feasible to readily combine data from different sources.

The TR-1 reconnaissance/surveillance aircraft.

The *2001 Mars Odyssey* used spectrometers and imagers to hunt for evidence of past or present water and volcanic activity on Mars.

Beyond the primitive methods of remote sensing our earliest ancestors used (ex.: standing on a high cliff or tree to view the landscape), the modern discipline arose with the development of flight. The balloonist G. Tournachon (alias Nadar) made photographs of Paris from his balloon in 1858. Messenger pigeons, kites, rockets and unmanned balloons were also used for early images. With the exception of balloons, these first, individual images were not particularly useful for map making or for scientific purposes.

Systematic aerial photography was developed for military surveillance and reconnaissance purposes beginning in World War I and reaching a climax during the Cold War with the use of modified combat aircraft such as the P-51, P-38, RB-66 and the F-4C, or specifically designed collection platforms such as the U2/TR-1, SR-71, A-5 and the OV-1 series both in overhead and stand-off collection. A more recent development is that of increasingly smaller sensor pods such as those used by law enforcement and the military, in both manned and unmanned platforms. The advantage of this approach is that this requires minimal modification to a given airframe. Later imaging technologies would include Infra-red, conventional, doppler and synthetic aperture radar.

The development of artificial satellites in the latter half of the 20th century allowed remote sensing to progress to a global scale as of the end of the Cold War. Instrumentation aboard various Earth observing and weather satellites such as Landsat, the Nimbus and more recent missions such as RADARSAT and UARS provided global measurements of various data for civil, research, and military purposes. Space probes to other planets have also provided the opportunity to conduct remote sensing studies in extraterrestrial environments, synthetic aperture radar aboard the Magellan spacecraft provided detailed topographic maps of Venus, while instruments aboard SOHO allowed studies to be performed on the Sun and the solar wind, just to name a few examples.

Recent developments include, beginning in the 1960s and 1970s with the development of image processing of satellite imagery. Several research groups in Silicon Valley including NASA Ames Research Center, GTE and ESL Inc. developed Fourier transform techniques leading to the first notable enhancement of imagery data.

The introduction of online web services for easy access to remote sensing data in the 21st century (mainly low/medium-resolution images), like Google Earth, has made remote sensing more familiar to the big public and has popularized the science.

## *Remote Sensing software*

Remote Sensing data is processed and analyzed with computer software, known as a remote sensing application. A large number of proprietary and open source applications exist to process remote sensing data. According to an NOAA Sponsored Research by Global Marketing Insights, Inc. the most used applications among Asian academic groups involved in remote sensing are as follows: ERDAS 36% (ERDAS IMAGINE 25% & ERMapper 11%); ESRI 30%; ITT Visual Information Solutions ENVI 17%; MapInfo 17%. Among Western Academic respondents as follows: ESRI 39%, ERDAS IMAGINE 27%, MapInfo 9%, AutoDesk 7%, ITT Visual Information Solutions ENVI 17%. Other important Remote Sensing Software packages include: TNTmips from MicroImages, PCI Geomatica made by PCI Geomatics, the leading remote sensing software package in Canada, IDRISI from Clark Labs, Image Analyst from Intergraph, RemoteView made by Overwatch Textron Systems, and the original object based image analysis software eCognition from Definiens. Dragon/ips is one of the oldest remote sensing packages still available, and is in some cases free. Open source remote sensing software includes GRASS GIS, QGIS, OSSIM, Opticks (software) and Orfeo toolbox.

# Chapter- 13

# Accelerometer
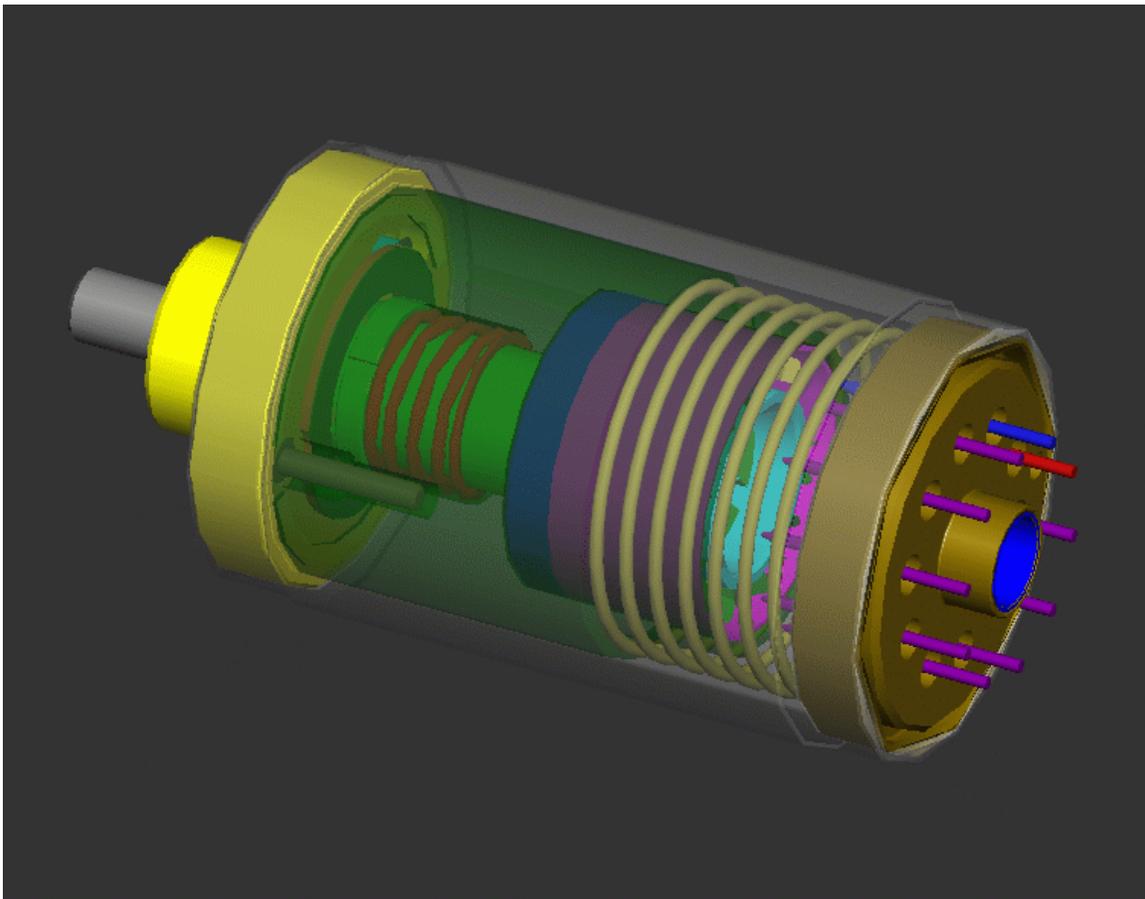


A depiction of an accelerometer designed at Sandia National Laboratories.

An **accelerometer** is a device that measures the proper acceleration of the device. This is *not necessarily* the same as the coordinate acceleration (change of velocity of the device in space), but is rather the type of acceleration associated with the phenomenon of weight experienced by a test mass that resides in the frame of reference of the accelerometer device. For an example of where these types of acceleration differ, an accelerometer will measure a value when sitting on the ground, because masses there have weights, even though they do not change velocity. However, an accelerometer in gravitational free fall

toward the center of the Earth will measure a value of zero because, even though its speed is increasing, it is in an inertial frame of reference, in which it is weightless.

An accelerometer thus measures **weight per unit of (test) mass**, a quantity also known as specific force, or g-force. Another way of stating this is that by measuring weight, an accelerometer measures the acceleration of the free-fall reference frame (inertial reference frame) relative to itself.

Most accelerometers do not display the value they measure, but supply it to other devices. Real accelerometers also have practical limitations in how quickly they respond to changes in acceleration, and cannot respond to changes above a certain frequency of change.

Single- and multi-axis models of accelerometer are available to detect magnitude and direction of the proper acceleration (or g-force), as a vector quantity, and can be used to sense orientation (because direction of weight changes), coordinate acceleration (so long as it produces g-force or a change in g-force), vibration, shock, and falling (a case where the proper acceleration changes, since it tends toward zero). Micromachined accelerometers are increasingly present in portable electronic devices and video game controllers, to detect the position of the device or provide for game input.

Pairs of accelerometers extended over a region of space can be used to detect differences (gradients) in the proper accelerations of frames of references associated with those points. These devices are called gradiometers, as they measure gradients in the gravitational field. Such pairs of accelerometers in theory may also be able to detect gravity waves.

## *Physical principles*

An accelerometer measures proper acceleration, which is the acceleration it experiences relative to freefall and is the acceleration felt by people and objects. Put another way, at any point in spacetime the equivalence principle guarantees the existence of a local inertial frame, and an accelerometer measures the acceleration relative to that frame. Such accelerations are popularly measured in terms of g-force.

An accelerometer at rest relative to the Earth's surface will indicate approximately 1 g *upwards*, because any point on the Earth's surface is accelerating upwards relative to the local inertial frame (the frame of a freely falling object near the surface). To obtain the acceleration due to motion with respect to the Earth, this "gravity offset" must be subtracted and corrections for effects caused by the Earth's rotation relative to the inertial frame.

The reason for the appearance of a gravitational offset is Einstein's equivalence principle, which states that the effects of gravity on an object are indistinguishable from acceleration. When held fixed in a gravitational field by, for example, applying a ground reaction force or an equivalent upward thrust, the reference frame for an accelerometer

(its own casing) accelerates upwards with respect to a free-falling reference frame. The effects of this acceleration are indistinguishable from any other acceleration experienced by the instrument, so that an accelerometer cannot detect the difference between sitting in a rocket on the launch pad, and being in the same rocket in deep space while it uses its engines to accelerate at 1 g. For similar reasons, an accelerometer will read *zero* during any type of free fall. This includes use in a coasting spaceship in deep space far from any mass, a spaceship orbiting the Earth, an airplane in a parabolic "zero-g" arc, or any free-fall in vacuum. Another example is free-fall at a sufficiently high altitude that atmospheric effects can be neglected.

However this does not include a (non-free) fall in which air resistance produces drag forces that reduce the acceleration, until constant terminal velocity is reached. At terminal velocity the accelerometer will indicate 1 g acceleration upwards. For the same reason a skydiver, upon reaching terminal velocity, does not feel as though he or she were in "free-fall", but rather experiences a feeling similar to being supported (at 1 g) on a "bed" of uprushing air.

Acceleration is quantified in the SI unit metres per second per second ($m/s^2$), in the cgs unit gal (Gal), or popularly in terms of g-force (*g*).

For the practical purpose of finding the acceleration of objects with respect to the Earth, such as for use in an inertial navigation system, a knowledge of local gravity is required. This can be obtained either by calibrating the device at rest, or from a known model of gravity at the approximate current position.

## *Structure*

Conceptually, an accelerometer behaves as a damped mass on a spring. When the accelerometer experiences an acceleration, the mass is displaced to the point that the spring is able to accelerate the mass at the same rate as the casing. The displacement is then measured to give the acceleration.

In commercial devices, piezoelectric, piezoresistive and capacitive components are commonly used to convert the mechanical motion into an electrical signal. Piezoelectric accelerometers rely on piezoceramics (e.g. lead zirconate titanate) or single crystals (e.g. quartz, tourmaline). They are unmatched in terms of their upper frequency range, low packaged weight and high temperature range. Piezoresistive accelerometers are preferred in high shock applications. Capacitive accelerometers typically use a silicon micro-machined sensing element. Their performance is superior in the low frequency range and they can be operated in servo mode to achieve high stability and linearity.

Modern accelerometers are often small *micro electro-mechanical systems* (MEMS), and are indeed the simplest MEMS devices possible, consisting of little more than a cantilever beam with a proof mass (also known as seismic mass). Damping results from the residual gas sealed in the device. As long as the Q-factor is not too low, damping does not result in a lower sensitivity.

Under the influence of external accelerations the proof mass deflects from its neutral position. This deflection is measured in an analog or digital manner. Most commonly, the capacitance between a set of fixed beams and a set of beams attached to the proof mass is measured. This method is simple, reliable, and inexpensive. Integrating piezoresistors in the springs to detect spring deformation, and thus deflection, is a good alternative, although a few more process steps are needed during the fabrication sequence. For very high sensitivities quantum tunneling is also used; this requires a dedicated process making it very expensive. Optical measurement has been demonstrated on laboratory scale.

Another, far less common, type of MEMS-based accelerometer contains a small heater at the bottom of a very small dome, which heats the air inside the dome to cause it to rise. A thermocouple on the dome determines where the heated air reaches the dome and the deflection off the center is a measure of the acceleration applied to the sensor.

Most micromechanical accelerometers operate *in-plane*, that is, they are designed to be sensitive only to a direction in the plane of the die. By integrating two devices perpendicularly on a single die a two-axis accelerometer can be made. By adding an additional *out-of-plane* device three axes can be measured. Such a combination always has a much lower misalignment error than three discrete models combined after packaging.

Micromechanical accelerometers are available in a wide variety of measuring ranges, reaching up to thousands of *g'*s. The designer must make a compromise between sensitivity and the maximum acceleration that can be measured.

## *Applications*

### Engineering

Accelerometers can be used to measure vehicle acceleration. They allow for performance evaluation of both the engine/drive train and the braking systems.

Accelerometers can be used to measure vibration on cars, machines, buildings, process control systems and safety installations. They can also be used to measure seismic activity, inclination, machine vibration, dynamic distance and speed with or without the influence of gravity. Applications for accelerometers that measure gravity, wherein an accelerometer is specifically configured for use in gravimetry, are called gravimeters.

Notebook computers equipped with accelerometers can contribute to the *Quake-Catcher Network* (QCN), a BOINC project aimed at scientific research of earthquakes.

### Biology

Accelerometers are also increasingly used in the biological sciences. High frequency recordings of bi-axial or tri-axial acceleration (>10 Hz) allows the discrimination of

behavioral patterns while animals are out of sight. Furthermore, recordings of acceleration allow researchers to quantify the rate at which an animal is expending energy in the wild, by either determination of limb-stroke frequency or measures such as overall dynamic body acceleration Such approaches have mostly been adopted by marine scientists due to an inability to study animals in the wild using visual observations, however an increasing number of terrestrial biologists are adopting similar approaches. This device can be connected to an amplifier to amplify the signal.

## Industry

Accelerometers are also used for machinery health monitoring of rotating equipment such as pumps, fans, rollers, compressors, and cooling towers,. Vibration monitoring programs are proven to save money, reduce downtime, and improve safety in plants worldwide by detecting conditions such as shaft misalignment, rotor imbalance, gear failure or bearing fault which can lead to costly repairs. Accelerometer vibration data allows the user to monitor machines and detect these faults before the rotating equipment fails. Vibration monitoring programs are utilized in industries such as automotive manufacturing, machine tool applications, pharmaceutical production, power generation and power plants, pulp and paper, food and beverage production, water and wastewater, hydropower, petrochemical and steel manufacturing.

## Building and structural monitoring

Accelerometers are used to measure the motion and vibration of a structure that is exposed to dynamic loads. Dynamic loads originate from a variety of sources including:

- Human activities - walking, running, dancing or skipping
- Working machines - inside a building or in the surrounding area
- Construction work - driving piles, demolition, drilling and excavating
- Moving loads on bridges
- Vehicle collisions
- Impact loads - falling debris
- Concussion loads - internal and external explosions
- Collapse of structural elements
- Wind loads and wind gusts
- Air blast pressure
- Loss of support because of ground failure
- Earthquakes and aftershocks

Measuring and recording how a structure responds to these inputs is critical for assessing the safety and viability of a structure. This type of monitoring is called Dynamic Monitoring.

## Medical applications

Zoll's AED Plus uses CPR-D•padz which contain an accelerometer to measure the depth of CPR chest compressions.

Within the last several years, Nike, Polar and other companies have produced and marketed sports watches for runners that include footpods, containing accelerometers to help determine the speed and distance for the runner wearing the unit.

In Belgium, accelerometer-based step counters are promoted by the government to encourage people to walk a few thousand steps each day.

Herman Digital Trainer uses accelerometers to measure strike force in physical training.

## Navigation

An **Inertial Navigation System** (INS) is a navigation aid that uses a computer and motion sensors (accelerometers) to continuously calculate via dead reckoning the position, orientation, and velocity (direction and speed of movement) of a moving object without the need for external references. Other terms used to refer to inertial navigation systems or closely related devices include **inertial guidance system**, **inertial reference platform**, and many other variations.

An accelerometer alone is unsuitable to determine changes in altitude over distances where the vertical decrease of gravity is significant, such as for aircraft and rockets. In the presence of a gravitational gradient, the calibration and data reduction process is numerically unstable.

## Transport

Accelerometers are used to detect apogee in both professional and in amateur rocketry.

Accelerometers are also being used in Intelligent Compaction rollers. Accelerometers are used alongside gyroscopes in inertial guidance systems.

One of the most common uses for MEMS accelerometers is in airbag deployment systems for modern automobiles. In this case the accelerometers are used to detect the rapid negative acceleration of the vehicle to determine when a collision has occurred and the severity of the collision. Another common automotive use is in electronic stability control systems, which use a lateral accelerometer to measure cornering forces. The widespread use of accelerometers in the automotive industry has pushed their cost down dramatically. Another automotive application is the monitoring of noise, vibration and harshness (NVH), conditions that cause discomfort for drivers and passengers and may also be indicators of mechanical faults.

Tilting trains use accelerometers and gyroscopes to calculate the required tilt.

## Vulcanology

Modern electronic accelerometers are used in remote sensing devices intended for the monitoring of active volcanos to detect the motion of magma

## Consumer electronics

Accelerometers are increasingly being incorporated into personal electronic devices.

### Motion input

Some smartphones, digital audio players and personal digital assistants contain accelerometers for user interface control; often the accelerometer is used to present landscape or portrait views of the device's screen, based on the way the device is being held.

Smartphones can download an Automatic Collision Notification (ACN) app such as My-911, similar to the Onstar AACN service, Ford Link's 911 Assist, Toyota's Safety Connect, Lexus Link, or BMW Assist. The phone's accelerometer detects crash-strength G-forces and automatically calls for assistance unless manually cancelled.

Nintendo's Wii video game console uses a controller called a Wii Remote that contains a three-axis accelerometer and was designed primarily for motion input. Users also have the option of buying an additional motion-sensitive attachment, the Nunchuk, so that motion input could be recorded from both of the user's hands independently.

The Sony PlayStation 3 uses the DualShock 3 remote which uses a six-axis accelerometer that can be used to make steering more realistic in racing games, such as Motorstorm and Burnout Paradise.

The Nokia 5500 sport features a 3D accelerometer that can be accessed from software. It is used for step recognition (counting) in a sport application, and for tap gesture recognition in the user interface. Tap gestures can be used for controlling the music player and the sport application, for example to change to next song by tapping through clothing when the device is in a pocket. Other uses for accelerometer in Nokia phones include Pedometer functionality in Nokia Sports Tracker. Some other devices provide the tilt sensing feature with a cheaper component, which is not a true accelerometer.

Sleep phase alarm clocks use accelerometric sensors to detect movement of a sleeper, so that it can wake the person when he/she is not in REM phase, therefore awakes more easily.

**Orientation sensing**

A number of 21st century devices use accelerometers to align the screen depending on the direction the device is held, i.e. switching between portrait and landscape modes. Such devices include many tablet PCs and some smartphones and digital cameras.

For example, Apple uses an LIS302DL accelerometer in the iPhone, iPod Touch and the 4th&5th generation iPod Nano allowing the device to know when it is tilted on its side. Third-party developers have expanded its use with fanciful applications such as electronic bobbleheads. The BlackBerry Storm phone was also an early user of this orientation sensing feature.

The Nokia N95 and Nokia N82 have accelerometers embedded inside them. It was primarily used as a tilt sensor for tagging the orientation to photos taken with the built-in camera, later thanks to a firmware update it became available to other applications.

As of January 2009, almost all new mobile phones and digital cameras contain at least a tilt sensor (sometimes an accelerometer) for the purpose of auto image rotation, motion-sensitive mini-games, and to correct shake when taking photographs.

**Image stabilization**

Camcorders use accelerometers for image stabilization. Still cameras use accelerometers for anti-blur capturing. The camera holds off snapping the CCD "shutter" when the camera is moving. When the camera is still (if only for a millisecond, as could be the case for vibration), the CCD is "snapped". An example application which has used such technology is the Glogger VS2, a phone application which runs on Symbian OS based phone with accelerometer such as Nokia N96. Some digital cameras, contain accelerometers to determine the orientation of the photo being taken and also for rotating the current picture when viewing.

**Device integrity**

Many laptops feature an accelerometer which is used to detect drops. If a drop is detected, the heads of the hard disk are parked to avoid data loss and possible head or disk damage by the ensuing shock.

## Gravimetry

A **gravimeter** or gravitometer, is an instrument used in gravimetry for measuring the local gravitational field. A gravimeter is a type of accelerometer, except that accelerometers are susceptible to all vibrations including noise, that cause oscillatory accelerations. This is counteracted in the gravimeter by integral vibration isolation and signal processing. Though the essential principle of design is the same as in accelerometers, gravimeters are typically designed to be much more sensitive than accelerometers in order to measure very tiny changes within the Earth's gravity, of 1 $g$. In

contrast, other accelerometers are often designed to measure 1000 $g$ or more, and many perform multi-axial measurements. The constraints on temporal resolution are usually less for gravimeters, so that resolution can be increased by processing the output with a longer "time constant".

# Chapter- 14

# Fiber Bragg Grating

A **fiber Bragg grating** (**FBG**) is a type of distributed Bragg reflector constructed in a short segment of optical fiber that reflects particular wavelengths of light and transmits all others. This is achieved by adding a periodic variation to the refractive index of the fiber core, which generates a wavelength specific dielectric mirror. A fiber Bragg grating can therefore be used as an inline optical filter to block certain wavelengths, or as a wavelength-specific reflector.
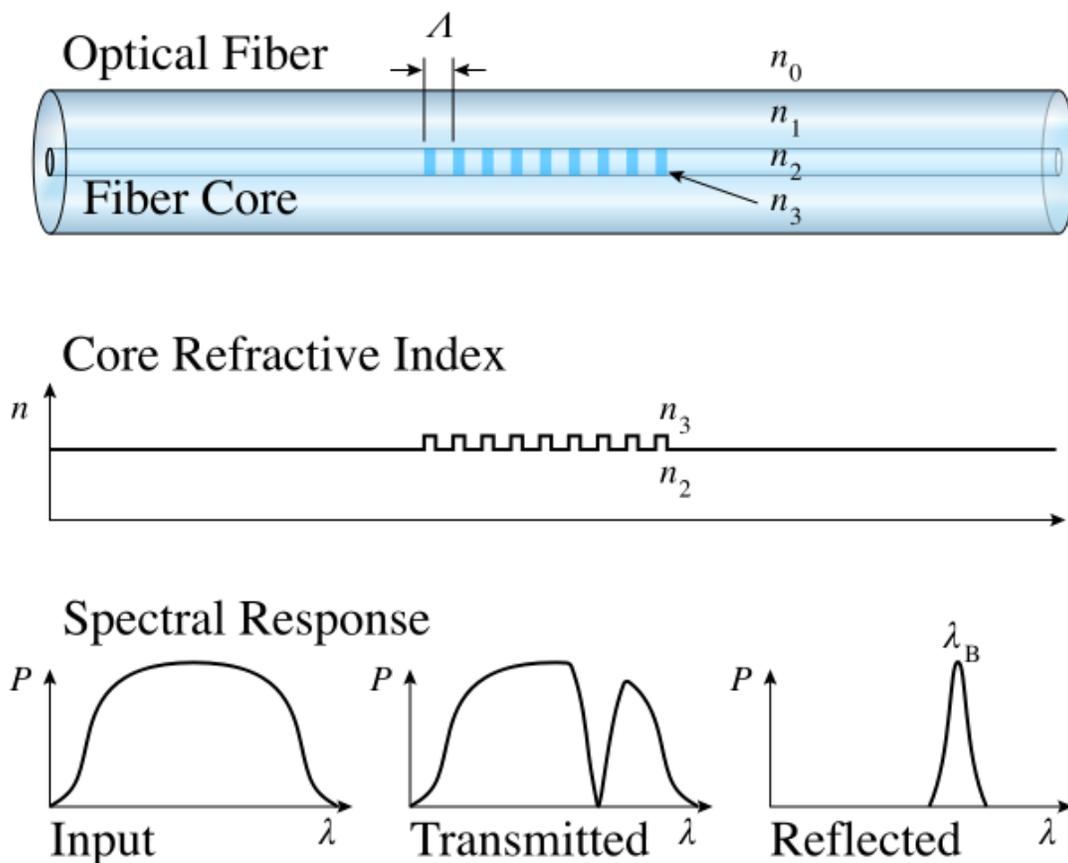


Figure 1: A Fiber Bragg Grating structure, with refractive index profile and spectral response

## *History*

The first in-fiber Bragg grating was demonstrated by Ken Hill in 1978. Initially, the gratings were fabricated using a visible laser propagating along the fiber core. In 1989, Gerald Meltz and colleagues demonstrated the much more flexible transverse holographic technique where the laser illumination came from the side of the fiber. This technique uses the interference pattern of ultraviolet laser light to create the periodic structure of the Bragg grating.

## *Manufacture*

Fiber Bragg gratings are created by "inscribing" or "writing" systematic (periodic or aperiodic) variation of refractive index into the core of a special type of optical fiber using an intense ultraviolet (UV) source such as a UV laser. Two main processes are used: *interference* and *masking*. The method that is preferable depends on the type of grating to be manufactured. A special germanium-doped silica fiber is used in the manufacture of fiber Bragg gratings. The germanium-doped fiber is photosensitive, in that the refractive index of the core changes with exposure to UV light, with the amount of the change a function of the intensity and duration of the exposure.

### Interference

The first manufacturing method, specifically used for uniform gratings, is the use of two-beam interference. Here the UV laser is split into two beams which interfere with each other creating a periodic intensity distribution along the interference pattern. The refractive index of the photosensitive fiber changes according to the intensity of light that it is exposed to. This method allows for quick and easy changes to the Bragg wavelength, which is directly related to the interference period and a function of the incident angle of the laser light.

### Photomask

A photomask having the intended grating features may also be used in the manufacture of fiber Bragg gratings. The photomask is placed between the UV light source and the photosensitive fiber. The shadow of the photomask then determines the grating structure based on the transmitted intensity of light striking the fiber. Photomasks are specifically used in the manufacture of chirped Fiber Bragg gratings, which cannot be manufactured using an interference pattern.

### Point-by-point

A single UV laser beam may also be used to 'write' the grating into the fiber point-by-point. Here, the laser has a narrow beam that is equal to the grating period. This method is specifically applicable to the fabrication of long period fiber gratings. Point-by-point is also used in the fabrication of tilted gratings.

## Production

Originally, the manufacture of the photosensitive optical fiber and the 'writing' of the fiber Bragg grating were done separately. Today, production lines typically draw the fiber from the preform and 'write' the grating, all in a single stage. As well as reducing associated costs and time, this also enables the mass production of fiber Bragg gratings. Mass production is in particular facilitating applications in smart structures utilizing large numbers (3000) of embedded fiber Bragg gratings along a single length of fiber.
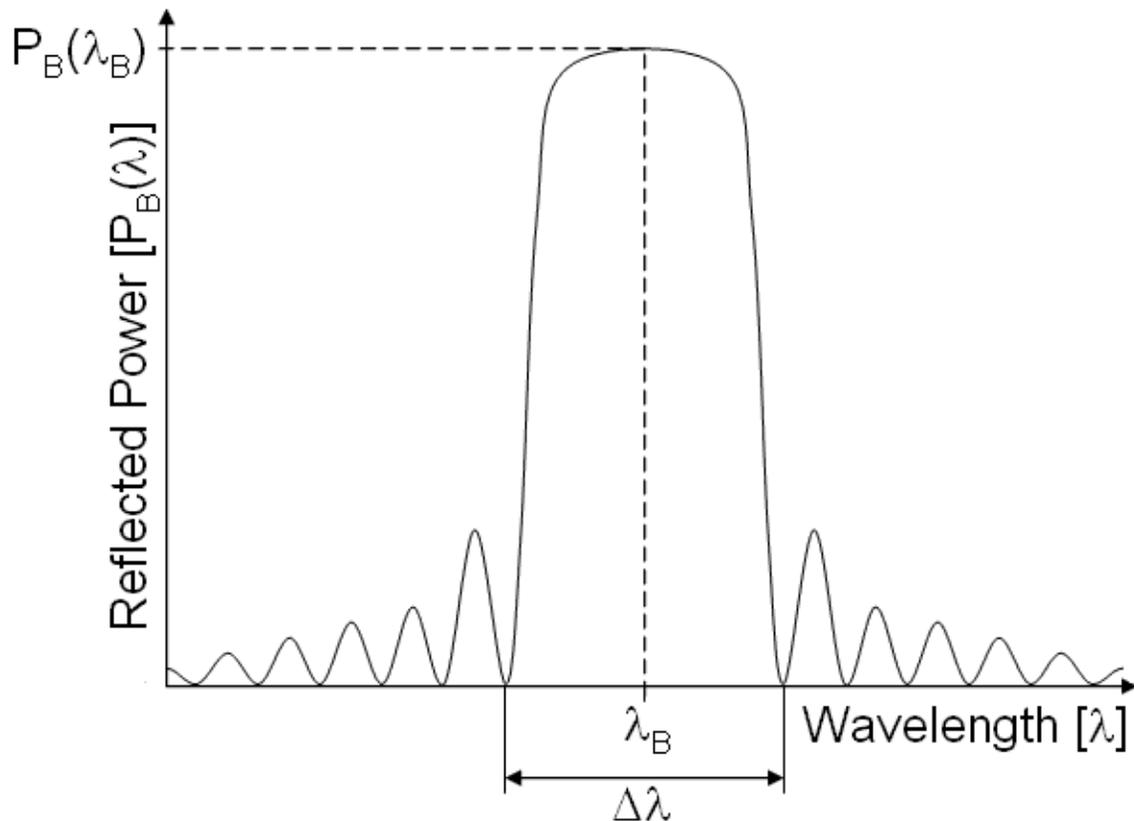
## *Theory*



Figure 2: FBGs reflected power as a function of wavelength

The fundamental principle behind the operation of a FBG, is Fresnel reflection. Where light traveling between media of different refractive indices may both reflect and refract at the interface.

The grating will typically have a sinusoidal refractive index variation over a defined length. The reflected wavelength ($\lambda_B$), called the Bragg wavelength, is defined by the relationship,

$$\lambda_B = 2n_e\Lambda,$$

where $n_e$ is the effective refractive index of the grating in the fiber core and $\Lambda$ is the grating period. The effective refractive index quantifies the velocity of propagating light as compared to its velocity in vacuum. $n_e$ depends not only on the wavelength but also (for multimode waveguides) on the mode in which the light propagates. For this reason, it is also called modal index.

The wavelength spacing between the first minima (nulls, see Fig. 2), or the bandwidth ($\Delta\lambda$), is given by,

$$\Delta\lambda = \left[\frac{2\delta n_0 \eta}{\pi}\right]\lambda_B$$

,

where $\delta n_0$ is the variation in the refractive index ($n_3 - n_2$), and $\eta$ is the fraction of power in the core.

The peak reflection ($P_B(\lambda_B)$) is approximately given by,

$$P_B(\lambda_B) \approx \tanh^2\left[\frac{N\eta(V)\delta n_0}{n}\right]$$

,

where $N$ is the number of periodic variations. The full equation for the reflected power ($P_B(\lambda)$), is given by,

$$P_B(\lambda) = \frac{\sinh^2\left[\eta(V)\delta n_0\sqrt{1-\Gamma^2}N\Lambda/\lambda\right]}{\cosh^2\left[\eta(V)\delta n_0\sqrt{1-\Gamma^2}N\Lambda/\lambda\right]-\Gamma^2}$$

,

where,

$$\Gamma(\lambda) = \frac{1}{\eta(V)\delta n_0}\left[\frac{\lambda}{\lambda_B}-1\right]$$

.

## Types of gratings

The term "type" in this context refers to the underlying photosensitivity mechanism by which grating fringes are produced in the fiber. The different methods of creating these fringes have a significant effect on physical attributes of the produced grating, particularly the temperature response and ability to withstand elevated temperatures. Thus far, five (or six) types of FBG have been reported with different underlying photosensitivity mechanisms. These are summarized below:

## Standard gratings or Type I gratings

Written in both hydrogenated and non-hydrogenated fiber of all types Type I gratings are usually known as standard gratings and are manufactured in fibers of all types under all hydrogenation conditions. Typically, the reflection spectra of a type I grating is equal to 1-T where T is the transmission spectra. This means that the reflection and transmission spectra are complementary and there is negligible loss of light by reflection into the cladding or by absorption. Type I gratings are the most commonly used of all grating types, and the only types of grating available off-the-shelf at the time of writing.

## Type IA gratings

- Regenerated grating written after erasure of a type I grating in hydrogenated germanosilicate fiber of all types

Type IA gratings were first published in 2001 during experiments designed to determine the effects of hydrogen loading on the formation of IIA gratings in germanosilicate fiber. In contrast to the anticipated blue shift of the peak Bragg wavelength, a large positive wavelength shift was measured. This type IA grating appeared once the conventional type I FBG had reached saturation followed by subsequent complete or partial erasure, and was therefore labeled as regenerated. It was also noted that the temperature coefficient of the regenerated grating was lower than a standard grating written under similar conditions.

There is a clear relationship between type IA and IIA gratings insomuch as their fabrication conditions are identical in all but one aspect: they both form in B/Ge co-doped fiber but IAs form only in hydrogenated fibers and IIAs form only in non-hydrogenated fibers.

## Type In (commonly known as Type IIA gratings)

- These are gratings that form as the negative part of the induced index change overtakes the positive part. It is usually associated with gradual relaxation of induced stress along the axis and/or at the interface. These gratings have recently been relabeled Type In (for Type 1 gratings with a negative index change; Type II label is reserved for those that are distinctly made above the damage threshold of the glass).

Later research by Xie et al. showed the existence of another type of grating with similar thermal stability properties to the type II grating. This grating exhibited a negative change in the mean index of the fiber and was termed type IIA. The gratings were formed in germanosilicate fibers with pulses from a frequency doubled XeCl pumped dye laser. It was shown that initial exposure formed a standard (type I) grating within the fiber which underwent a small red shift before being erased. Further exposure showed that a grating reformed which underwent a steady blue shift whilst growing in strength.

## Regenerated gratings

These are gratings that are reborn at higher temperatures after erasure of gratings, usually Type I gratings and usually, though not always, in the presence of hydrogen. They have been interpreted in different ways including dopant diffusion (oxygen being the most popular current interpretation) and glass structural change. Recent work has shown that there exists a regeneration regime beyond diffusion where gratings can be made to operate at temperatures in excess of 1295C, outperforming even Type II femtosecond gratings. These are extremely attractive for ultra high temperature applications.

## Type II gratings

- Damage written gratings inscribed by multiphoton excitation with higher intensity lasers that exceed the damage threshold of the glass. Lasers employed are usually pulsed in order to reach these intensities. They include recent developments in multiphoton excitation using femtosecond pulses where the short timescales (commensurate on a timescale similar to local relaxation times) offer unprecedented spatial localization of the induced change. The amorphous network of the glass is usually transformed via a different ionization and melting pathway to give either higher index changes or create, through micro-explosions, voids surrounded by more dense glass.

Archambault et al. showed that it was possible to inscribe gratings of ~100% (>99.8%) reflectance with a single UV pulse in fibers on the draw tower. The resulting gratings were shown to be stable at temperatures as high as 800˚C (up to 1000C in some cases, and higher with femtosecond laser inscription). The gratings were inscribed using a single 40mJ pulse from an excimer laser at 248 nm. It was further shown that a sharp threshold was evident at ~30mJ; above this level the index modulation increased by more than two orders of magnitude, whereas below 30mJ the index modulation grew linearly with pulse energy. For ease of identification, and in recognition of the distinct differences in thermal stability, they labeled gratings fabricated below the threshold as type I gratings and above the threshold as type II gratings. Microscopic examination of these gratings showed a periodic damage track at the grating's site within the fiber ; hence type II gratings are also known as damage gratings. However, these cracks can be very localized so as to not play a major role in scattering loss if properly prepared

**_Grating structure_**

## 1) Uniform Fiber Bragg Grating



## 2) Chirped Fiber Bragg Grating



## 3) Tilted Fiber Bragg Grating



## 4) Superstructure Fiber Bragg Grating



Figure 3: Structure of the refractive index change in a uniform FBG (1), a chirped FBG (2), a tilted FBG (3), and a superstructure FBG (4).
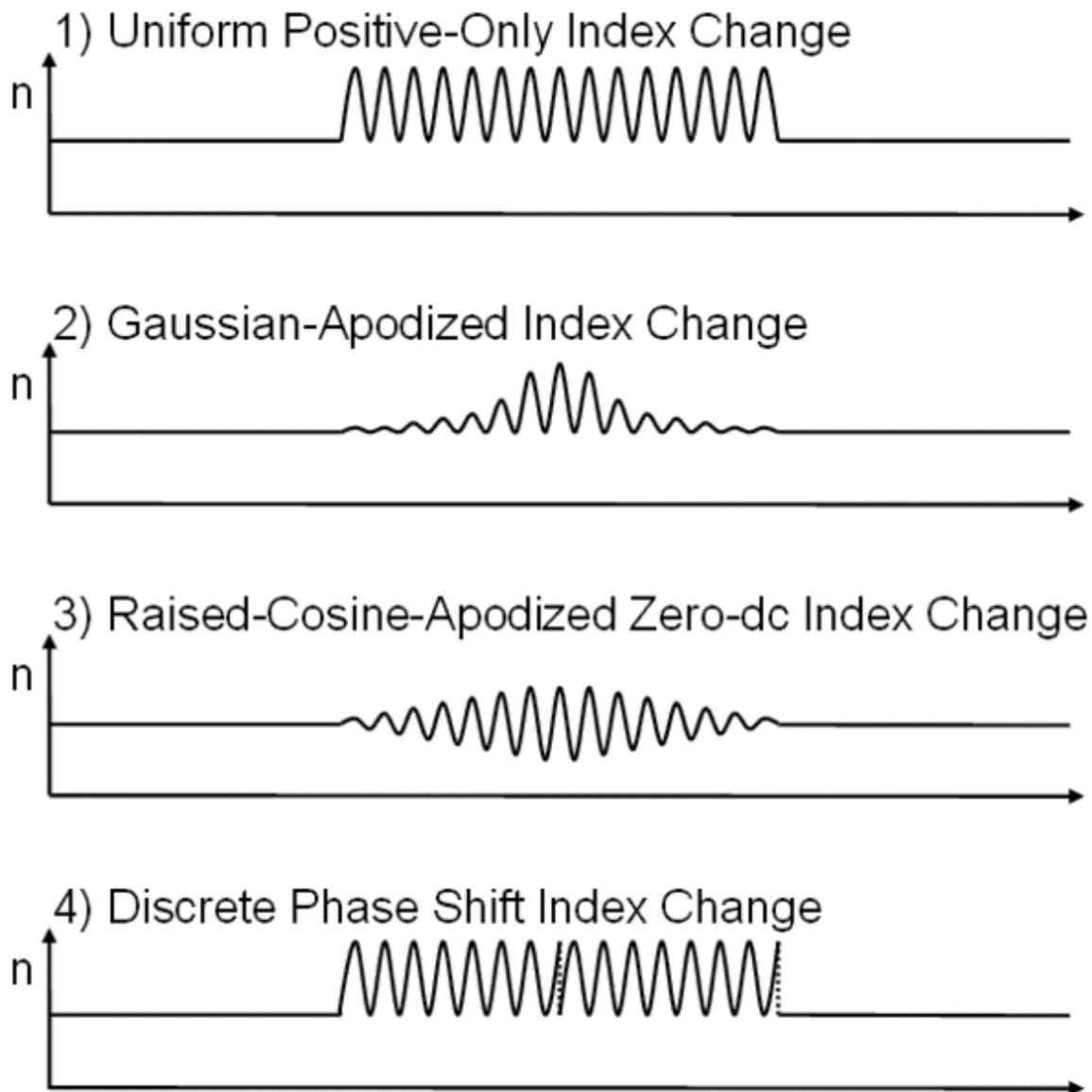
Figure 4: Refractive index profile in the core of, 1) a uniform positive-only FBG, 2) a Gaussian-apodized FBG, 3) a raised-cosine-apodized FBG with zero-dc change, and 4) a discrete phase shift FBG.

The structure of the FBG can vary via the refractive index, or the grating period. The grating period can be uniform or graded, and either localised or distributed in a superstructure. The refractive index has two primary characteristics, the refractive index profile, and the offset. Typically, the refractive index profile can be uniform or apodized, and the refractive index offset is positive or zero.

There are six common structures for FBGs;

1. uniform positive-only index change,
2. Gaussian apodized,

3. raised-cosine apodized,
4. chirped,
5. discrete phase shift, and
6. superstructure.

The first complex grating was made by J. Canning in 1994. This supported the development of the first distributed feedback (DFB) fiber lasers, and also laid the groundwork for most complex gratings that followed, including the sampled gratings first made by Peter Hill and colleagues in Australia.

## Apodized gratings

There are basically two quantities that control the properties of the FBG. These are the grating length, $L_g$, given as

$$L_g = N\Lambda,$$

and the grating strength, $\delta n_0\ \eta$. There are, however, three properties that need to be controlled in a FBG. These are the reflectivity, the bandwidth, and the side-lobe strength. As shown above, the bandwidth depends on the grating strength, and not the grating length. This means the grating strength can be used to set the bandwidth. The grating length, effectively $N$, can then be used to set the peak reflectivity, which depends on both the grating strength and the grating length. The result of this is that the side-lobe strength cannot be controlled, and this simple optimisation results in significant side-lobes. A third quantity can be varied to help with side-lobe suppression. This is apodization of the refractive index change. The term apodization refers to the grading of the refractive index to approach zero at the end of the grating. Apodized gratings offer significant improvement in side-lobe suppression while maintaining reflectivity and a narrow bandwidth. The two functions typically used to apodize a FBG are Gaussian and raised-cosine.

## Chirped fiber Bragg gratings

The refractive index profile of the grating may be modified to add other features, such as a linear variation in the grating period, called a chirp. The reflected wavelength changes with the grating period, broadening the reflected spectrum. A grating possessing a chirp has the property of adding dispersion—namely, different wavelengths reflected from the grating will be subject to different delays. This property has been used in the development of phased-array antenna systems and polarization mode dispersion compensation, as well.

## Tilted fiber Bragg gratings

In standard FBGs, the grading or variation of the refractive index is along the length of the fiber (the optical axis), and is typically uniform across the width of the fiber. In a

tilted FBG (TFBG), the variation of the refractive index is at an angle to the optical axis. The angle of tilt in a TFBG has an effect on the reflected wavelength, and bandwidth.

## Long-period gratings

Typically the grating period is the same size as the Bragg wavelength, as shown above. For a grating that reflects at 1500 nm, the grating period is 500 nm, using a refractive index of 1.5. Longer periods can be used to achieve much broader responses than are possible with a standard FBG. These gratings are called long-period fiber grating. They typically have grating periods on the order of 100 micrometers, to a millimeter, and are therefore much easier to manufacture.

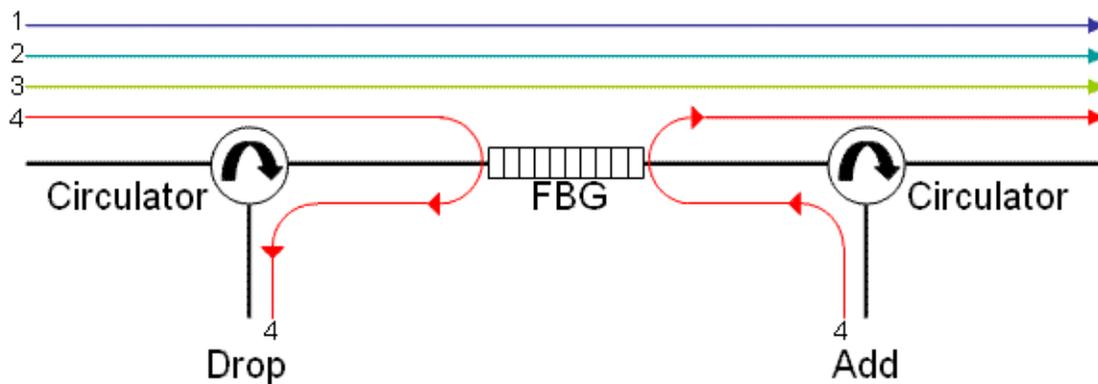## *Applications*

## Communications



Figure 5: Optical add-drop multiplexer.

The primary application of fiber Bragg gratings is in optical communications systems. They are specifically used as notch filters. They are also used in optical multiplexers and demultiplexers with an optical circulator, or Optical Add-Drop Multiplexer (OADM). Figure 5 shows 4 channels, depicted as 4 colours, impinging onto a FBG via an optical circulator. The FBG is set to reflect one of the channels, here channel 4. The signal is reflected back to the circulator where it is directed down and dropped out of the system. Since the channel has been dropped, another signal on that channel can be added at the same point in the network.

A demultiplexer can be achieved by cascading multiple drop sections of the OADM, where each drop element uses a FBG set to the wavelength to be demultiplexed. Conversely, a multiplexer can be achieved by cascading multiple add sections of the OADM. FBG demultiplexers and OADMs can also be tunable. In a tunable demultiplexer or OADM, the Bragg wavelength of the FBG can be tuned by strain applied by a piezoelectric transducer. The sensitivity of a FBG to strain is discussed below in fiber Bragg grating sensors.

## Fiber Bragg grating sensors

As well as being sensitive to strain, the Bragg wavelength is also sensitive to temperature. This means that fiber Bragg gratings can be used as sensing elements in optical fiber sensors. In a FBG sensor, the measurand causes a shift in the Bragg wavelength, $\Delta\lambda_B$. The relative shift in the Bragg wavelength, $\Delta\lambda_B / \lambda_B$, due to an applied strain ($\varepsilon$) and a change in temperature ($\Delta T$) is approximately given by,

$$\left[\frac{\Delta\lambda_B}{\lambda_B}\right] = C_S\epsilon + C_T\Delta T$$

,

or,

$$\left[\frac{\Delta\lambda_B}{\lambda_B}\right] = (1 - p_e)\epsilon + (\alpha_\Lambda + \alpha_n)\Delta T$$

.

Here, $C_S$ is the *coefficient of strain*, which is related to the *strain optic coefficient $p_e$*. Also, $C_T$ is the *coefficient of temperature*, which is made up of the *thermal expansion coefficient* of the optical fiber, $\alpha_\Lambda$, and the *thermo-optic coefficient*, $\alpha_n$.

Fiber Bragg gratings can then be used as direct sensing elements for strain and temperature. They can also be used as transduction elements, converting the output of another sensor, which generates a strain or temperature change from the measurand, for example fiber Bragg grating gas sensors use an absorbent coating, which in the presence of a gas expands generating a strain, which is measurable by the grating. Technically, the absorbent material is the sensing element, converting the amount of gas to a strain. The Bragg grating then transduces the strain to the change in wavelength.

Specifically, fiber Bragg gratings are finding uses in instrumentation applications such as seismology, pressure sensors for extremely harsh environments, and as downhole sensors in oil and gas wells for measurement of the effects of external pressure, temperature, seismic vibrations and inline flow measurement. As such they offer a significant advantage over traditional electronic gauges used for these applications in that they are less sensitive to vibration or heat and consequently are far more reliable. In the 1990s, investigations were conducted for measuring strain and temperature in composite materials for aircraft and helicopter structures.

**Chapter- 15**

# Cellular Confinement

**Cellular Confinement Systems** (CCS, also known as **geocells**) are widely used in construction for erosion control, soil stabilization on flat ground and steep slopes, channel protection, and structural reinforcement for load support and earth retention. Typical cellular confinement systems are made with ultrasonically-welded high-density polyethylene (HDPE) or other polymeric alloy strips that are expanded on-site to form a honeycomb-like structure which may be filled with sand, soil, rock or concrete.

## *History of Cellular Confinement*

Research and development of cellular confinement systems (CCS) began with the U.S. Army Corps of Engineers in September 1975 to test the feasibility of constructing tactical bridge approach roads over soft ground. Engineers discovered that sand-confinement systems performed better than conventional crushed stone sections. They concluded that a sand-confinement system could be developed that would provide an expedient construction technique for building approach roads over soft ground and that the system would not be adversely affected by wet weather conditions.  These early efforts led to the civilian commercialization of the product by the Presto Products Company. to produce the first cellular confinement system from high density polyethylene (HDPE) that was light weight, strong and durable. This new cellular confinement system was used first for load support applications in the United States in the early 1980s; second for slope erosion control and channel lining in the United States in 1984 and; third for earth retention in Canada in 1986. Research on cellular confinement in these application areas also started during the 1980s.

Research by Drs. Bathurst and Jarrett discovered that cellular confinement reinforced gravel bases are "equivalent to about twice the thickness of unreinforced gravel bases" when placed over a saturated peat sub-base. Further, 1.25 mm (50 mil) HDPE performed better than single sheet reinforcement schemes (geotextiles and geogrids) and was more effective in reducing lateral spreading of the infill material under loading than conventional reinforced bases. In terms of the effectiveness of confinement, geocells have more attractive features due to its 3D structure than any other planar geosynthetic reinforcement. Since this early work, the results of large-scale triaxial test on isolated geocells has demonstrated that cellular confinement imparts apparent cohesion to cohesionless compacted granular material on the order of 169 kPa - 190 kPa (3500 psf - 4000 psf). Cellular confinement systems are now recognized as an important technology

when applied to load support (Webster, 1986 and Bathurst & Jarrett, 1988) under roads and rail lines, gravity and reinforced earth retaining wall systems (Crowe, Bathurst & Alston, 1989), (Bathurst, Crowe & Zehaluk, 1993), slope stabilization and erosion control, channel lining systems (Engel, P. & Flato, G. 1987) (Simons, Li & Associates, 1988) (Wu & Austin, 1992) and other innovative uses.

## *From HDPE to new polymeric alloys*

Competition in the business has led to questionable assertions to differentiate cellular confinement materials. While traditional HDPE based geocells may deform in small measure plastically over time, questions about their effectiveness for long-term reinforcement are for the most part overstated, because although geocells from advanced polymeric alloys can provide stiffness and confinement, they do not enable new, critical applications. Tens of thousands of installations without failure are in service - many for over thirty years. However, newcomers to the industry are attempting to create concerns about long standing standards of performance. The untested systems have focused on the development of advanced polymeric alloys that claim exponentially higher fatigue limits and resistance to environmental factors, particularly high temperatures well over 120 degrees F. Such properties mean very little as cellular confinement never reach such high temperatures as they are buried into the earth in their applications. Of course, it is understood by knowledgeable Engineers that even in the heat of the summer day, the earth remains relatively cool. Therefore, The so called alloys have no real additional benefit beyond those made of HDPE. Further, such "alloys" are made from less expensive materials and allow for less flexibility of finished product creating some problems for installations crews in cool climates. More predictable and reliable performance is not generally found from advanced polymeric alloy.

## *How it works*

A Cellular Confinement System when infilled with compacted soil creates a new composite entity that possesses enhanced mechanical and geotechnical properties. When the soil contained within a geocell is subjected to pressure, it causes lateral stresses on perimeter cell walls. The 3D zone of confinement reduces the lateral movement of soil particles while vertical loading on the contained infill results in high lateral stress and resistance on the cell-soil interface. These increase the shear strength of the confined soil, which:

- Creates a stiff mattress or slab to distribute the load over a wider area
- Reduces punching of soft soil
- Increases shear resistance and bearing capacity
- Decreases deformation

Confinement from adjacent cells provides additional resistance against the loaded cell through passive resistance, while lateral expansion of the infill is restricted by high hoop strength. Compaction is maintained by the confinement resulting in long term reinforcement.

**Applications**

## Load Support

Cellular Confinement Systems (CCS) have been used to improve the performance of both paved and unpaved roads by reinforcing the soil in the subgrade-base interface or within the base course. The effective load distribution of CCS creates a strong, stiff cellular mattress. This 3D mattress reduces vertical differential settlement into soft subgrades, improves shear strength, and enhances load-bearing capacity, while reducing the amount of aggregate material required to extend the service life of roads. As a composite system, cellular confinement strengthens the aggregate infill, thereby simultaneously enabling the use of poorly graded inferior material (e.g. local native soils, quarry waste or recycled materials) for infill as well as reducing the structural support layer thickness. Typical load support applications include reinforcement of base and subbase layers in flexible pavements, including: asphalt pavements; unpaved access, service and haul roads; railway substructure and ballast confinement; working platforms in intermodal ports; airport runways and aprons, permeable pavements; pipeline road support; green parking facilities and emergency access areas.

## Slope and Channel Protection

The three-dimensional lateral confinement of CCS along with anchoring techniques ensures the long-term stability of slopes using vegetated topsoil, aggregate or concrete surfacing (if exposed to severe mechanical and hydraulic pressures). The enhanced drainage, frictional forces and cell-soil-plant interaction of CCS prevents downslope movement and limits the impact of raindrops, channeling and hydraulic shear stresses. The perforations in the 3D cells allow the passage of water, nutrients and soil organisms. This encourages plant growth and root interlock, which further stabilizes the slope and soil mass, and facilitates landscape rehabilitation. Typical applications include: construction cut and fill slopes and stabilization; road and rail embankments; pipeline stabilization and storage facility berms; quarry and mine site restoration; channel and coastline structures.

## Earth Retention

CCS systems provide steep vertical mechanically stabilized earth structures (either gravity or reinforced walls) for steep faces, walls and irregular topography. Construction of CCS earth retention is simiplified as each layer is structurally sound thereby providing access for equipment and workers, while eliminating the need for concrete formwork and curing. Local soil can be used for infill, while the outer faces enable a green or tan fascia of the horizontal terraces/rows. In addition research by Leshchinsky, D. (2009) has demonstrated superior seismic stability of CCS systems in earthquake simulation tests.

### Reservoirs and Landfills

CCS provides membrane liner protection, while creating stable soil, berms and slopes, for non-slip protection and durable impoundment of liquids and waste. Infill treatment depends on the contained materials: concrete for ponds and reservoirs; gravel for landfill drainage and leachates, vegetated infill for landscape rehabilitation. Concrete work is efficient and controlled as CCS functions as ready-made forms; CCS with concrete forms a flexible slab that accommodates minor subgrade movement and prevents cracking. In medium and low flow-velocities, CCS with geomembranes and gravel cover can be used to create impermeable channels, thereby eliminating the need for concrete.

### Sustainable Construction

CCS is a green solution that makes civil infrastructure projects more sustainable. In load support applications, by reducing the amount and type of infill needed to reinforce soil, the usage of haul and earthmoving equipment is reduced. This in turn decreases fuel use, pollution and the carbon footprint, and at the same time minimizes on-site disruption from dust, erosion and runoff. When used for slope applications, perforated geocells provides excellent soil protection, water drainage and growth stratum for plants. The long-term design life of advanced CCS technology means that maintenance and the associated environmental costs are significantly reduced, as are long-term economic costs.

### Research

In the field and laboratory tests, CCS has proven to significantly increase the lifetime of the pavement and decrease road and railway substructure maintenance. Research on cellular confinement in these application areas focused on three ways: 1) use of triaxial or resilient modulus cells to investigate the confinement effect on apparent cohesion or reducing plastic deformation; 2) the use of laboratory model tests to investigate the reinforcement effect on bearing capacity and reducing settlement under static or dynamic loading; and 3) full-scale trafficking tests to investigate the overall effect, as reducing rut depth and prolonging road life. An extensive review of existing literature on 26 CCS research studies including triaxial compression tests, laboratory model tests, and field tests, researchers concluded that: 1) Geocell reinforced bases always performed better than unreinforced bases with the same thickness in terms of the bearing capacity under static and repeated loading; 2) Proper tensile and seam strengths are needed for geocells to provide effective reinforcement. Geocells made of high strength materials typically had higher bearing capacity; 3) There exist optimum values of the geocell height/width ratio and the loading area width/geocell width ratio; 4) Geocells showed excellent performance as compared with 2D planar reinforcement; 5) High-quality infill materials yield high bearing capacity of geocell-reinforced bases.

# Chapter- 16

# Wireless Sensor Network
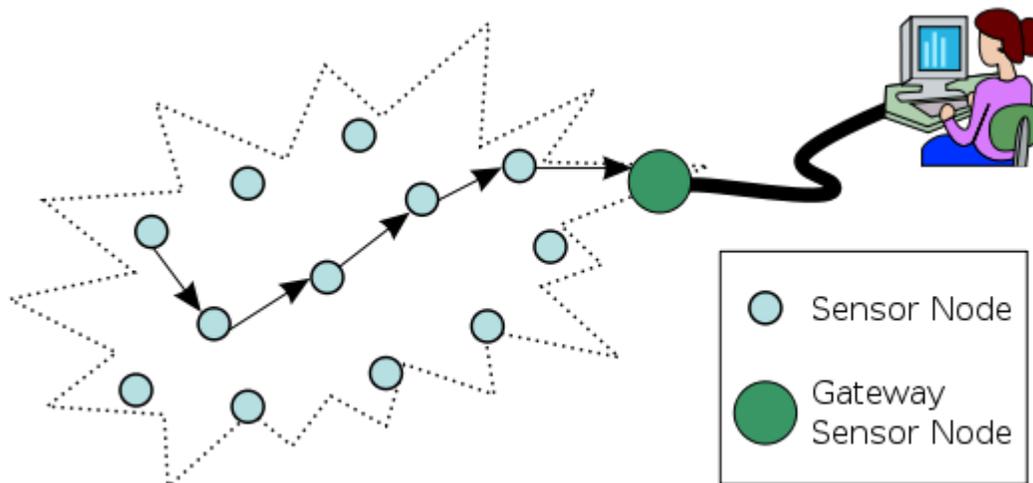
Typical Multihop Wireless Sensor Network Architecture

A **Wireless Sensor Network** (WSN) consists of spatially distributed autonomous sensors to *monitor* physical or environmental conditions, such as temperature, sound, vibration, pressure, motion or pollutants., and to cooperatively pass their data through the network to a main location. The more modern networks are bi-directional, enabling also to *control* the activity of the sensors. The development of wireless sensor networks was motivated by military applications such as battlefield surveillance; today such networks are used in many industrial and consumer application, such as industrial process monitoring and control, machine health monitoring, environment and habitat monitoring, healthcare applications, home automation, and traffic control.

The WSN is built of "nodes" - from a few to several hundreds or even thousands, where each node is connected to one (or sometimes several) sensors. Each such sensor network node has typically several parts: a radio transceiver with an internal antenna or connection to an external antenna, a microcontroller, an electronic circuit for interfacing with the sensors and an energy source, usually a battery or an embedded form of energy harvesting. A sensor node might vary in size from that of a shoebox down to the size of a grain of dust, although functioning "motes" of genuine microscopic dimensions have yet to be created. The cost of sensor nodes is similarly variable, ranging from hundreds of dollars to a few pennies, depending on the complexity of the individual sensor nodes.

Size and cost constraints on sensor nodes result in corresponding constraints on resources such as energy, memory, computational speed and communications bandwidth. The topology of the WSNs can vary from a simple star network to an advanced multi-hop wireless mesh network. The propagation technique between the hops of the network can be routing or flooding.

In computer science and telecommunications, wireless sensor networks are an active research area with numerous workshops and conferences arranged each year.

## Area monitoring

Area monitoring is a common application of WSNs. In area monitoring, the WSN is deployed over a region where some phenomenon is to be monitored. A military example is the use of sensors to detect enemy intrusion; a civilian example is the geo-fencing of gas or oil pipelines.

When the sensors detect the event being monitored (heat, pressure), the event is reported to one of the base stations, which then takes appropriate action (e.g., send a message on the internet or to a satellite). Similarly, wireless sensor networks can use a range of sensors to detect the presence of vehicles ranging from motorcycles to train cars.

## Environmental monitoring

A number of WSNs have been deployed for environmental monitoring.

### Air pollution monitoring

Wireless sensor networks have been deployed in several cities (Stockholm, London or Brisbane) to monitor the concentration of dangerous gases for citizens. The sensor nodes can control important parameters like CO, CO2, NO2 or CH4, which are generated by vehicles and industry, and have a severe impact on the human health. This way, the public institutions have a good tool to design plans to reduce pollution, improve the air quality and ensure the compliance with current legislation.

### Forest fires detection

A network of Sensor Nodes can be installed in a forest to control when a fire has started. The nodes will be equipped with sensors to control temperature, humidty and gases which are produced by fire in the trees or vegetation. The early detection is crucial for a successful action of the firefighters; thanks to Wireless Sensor Networks, the fire brigade will be able to know when a fire is started and how it is spreading.

### Greenhouse monitoring

Wireless sensor networks are also used to control the temperature and humidity levels inside commercial greenhouses. When the temperature and humidity drops below

specific levels, the greenhouse manager must be notified via e-mail or cell phone text message, or host systems can trigger misting systems, open vents, turn on fans, or control a wide variety of system responses.

**Landslide detection**

A landslide detection system, makes use of a wireless sensor network to detect the slight movements of soil and changes in various parameters that may occur before or during a landslide. And through the data gathered it may be possible to know the occurrence of landslides long before it actually happens.

## Industrial monitoring

**Machine health monitoring**

Wireless sensor networks have been developed for machinery condition-based maintenance (CBM)as they offer significant cost savings and enable new functionalities. In wired systems, the installation of enough sensors is often limited by the cost of wiring. Previously inaccessible locations, rotating machinery, hazardous or restricted areas, and mobile assets can now be reached with wireless sensors.

## Water/Wastewater monitoring

There are many opportunities for using wireless sensor networks within the water/wastewater industries. Facilities not wired for power or data transmission can be monitored using industrial wireless I/O devices and sensors powered using solar panels or battery packs.

**Landfill ground well level monitoring and pump counter**

Wireless sensor networks can be used to measure and monitor the water levels within all ground wells in the landfill site and monitor leachate accumulation and removal. A wireless device and submersible pressure transmitter monitors the leachate level. The sensor information is wirelessly transmitted to a central data logging system to store the level data, perform calculations, or notify personnel when a service vehicle is needed at a specific well.

**Agriculture**

Using wireless sensor networks within the agricultural industry is increasingly common; using a wireless network frees the farmer from the maintenance of wiring in a difficult environment. Gravity feed water systems can be monitored using pressure transmitters to monitor water tank levels, pumps can be controlled using wireless I/O devices, and water use can be measured and wirelessly transmitted back to a central control center for billing. Irrigation automation enables more efficient water use and reduces waste.

**Fleet monitoring**

It is possible to put a node on-board of each vehicle of a fleet. The node gathers its position via the GPS module, and reports its coordinates so that the location is tracked in real-time. The nodes can be connected to temperature sensors to avoid any disruption of the cold chain, helping to ensure the safety of food, pharmaceutical and chemical shipments. In situations where there is not reliable GPS coverage, like inside buildings, garages and tunnels, using information from GSM cells is an alternative for to GPS localization.

## *Characteristics*

The main characteristics of a WSN include:

- Power consumption constrains for nodes using batteries or energy harvesting
- Ability to cope with node failures
- Mobility of nodes
- Dynamic network topology
- Communication failures
- Heterogeneity of nodes
- Scalability to large scale of deployment
- Ability to withstand harsh environmental conditions
- Easy of use
- Unattended operation.

Sensor nodes can be imagined as small computers, extremely basic in terms of their interfaces and their components. They usually consist of a *processing unit* with limited computational power and limited memory, *sensors* or MEMS (including specific conditioning circuitry), a *communication device* (usually radio transceivers or alternatively optical), and a power source usually in the form of a battery. Other possible inclusions are energy harvesting modules, secondary ASICs, and possibly secondary communication devices (e.g. RS-232 or USB).

The base stations are one or more distinguished components of the WSN with much more computational, energy and communication resources. They act as a gateway between sensor nodes and the end user as they typically forward data from the WSN on to a server. Other special components in routing based networks are routers, designed to compute, calculate and distribute the routing tables. Many techniques are used to connect to the outside world including mobile phone networks, satellite phones, radio modems, high power WiFi links etc.

## *Platforms*

## Standards and specifications

Several standards are currently either ratified or under development for wireless sensor networks. There are a number of standardization bodies in the field of WSNs. The IEEE focuses on the physical and MAC layers; the Internet Engineering Task Force works on layers 3 and above. In addition to these, bodies such as the International Society of Automation provide vertical solutions, covering all protocol layer. Finally, there are also several non-standard, proprietary mechanisms and specifications.

Standards are used far less in WSNs than in other computing systems. However predominant standards commonly used in WSN communications include:

- ISA100
- IEEE 1451
- ZigBee / 802.15.4
- IEEE 802.11

## Hardware

The main challenge in a WSN is to produce *low cost* and *tiny* sensor nodes. There are an increasing number of small companies producing WSN hardware and the commercial situation can be compared to home computing in the 1970s. Many of the nodes are still in the research and development stage, particularly their software. Also inherent to sensor network adoption is the use very low power method for data acquisition.

## Software

Energy is the scarcest resource of WSN nodes, and it determines the lifetime of WSNs. WSNs are meant to be deployed in large numbers in various environments, including remote and hostile regions, with ad-hoc communications as key. For this reason, algorithms and protocols need to address the following issues:

- Lifetime maximization
- Robustness and fault tolerance
- Self-configuration

Some of the important topics in WSN software research are:

- Operating systems
- Security
- Mobility
- Usability - human interface for deployment and management, debugging and end-user control

- Middleware - the design of middle-level primitives between high level software and the systems

**Operating systems**

Operating systems for wireless sensor network nodes are typically less complex than general-purpose operating systems. They more strongly resemble embedded systems, for two reasons. First, wireless sensor networks are typically deployed with a particular application in mind, rather than as a general platform. Second, a need for low costs and low power leads most wireless sensor nodes to have low-power microcontrollers ensuring that mechanisms such as virtual memory either unnecessary or too expensive to implement.

It is therefore possible to use embedded operating systems such as eCos or uC/OS for sensor networks. However, such operating systems are often designed with real-time properties.

TinyOS is perhaps the first operating system specifically designed for wireless sensor networks. TinyOS is based on an event-driven programming model instead of multithreading. TinyOS programs are composed into *event handlers* and *tasks* with run to completion-semantics. When an external event occurs, such as an incoming data packet or a sensor reading, TinyOS signals the appropriate event handler to handle the event. Event handlers can post tasks that are scheduled by the TinyOS kernel some time later.

LiteOS is a newly developed OS for wireless sensor networks, which provides UNIX like abstraction and support for C programming language. Contiki is an OS which uses a simpler programming style in C while providing advances such as 6LoWPAN and proto-threads.

**Algorithms**

The *algorithmic* approach to modelling, simulating and analyzing WSNs differentiates itself from the *protocol* approach by the fact that the idealised mathematical models used are more general and easier to analyze. However, they are sometimes less realistic than the models used for protocol design, since an algorithmic approach often neglects timing issues, protocol overhead, the routing initiation phase and sometimes distributed implementation of the algorithms.

## Discussion of WSN simulators

There are network simulator platforms specifically designed to model and simulate Wireless Sensor Networks, like TOSSIM, which is a part of TinyOS and COOJA which is a part of Contiki. Traditional network simulators like ns-2 have also been used. Ns-3, which is an upgrade over Ns-2 is expected to be released shortly, also features WSN libraries

Network Simulators like QualNet, Opnet, NetSim and NS2 can be used to simulate Wireless Sensor Network. Other simulators, like IDEA1 -based on SystemC- have hardware-level librairies that permits system-level simulations by taking low-level constraints into account.

Based on Matlab, the Prowler (Probabilistic Wireless Network Simulator) toolbox is available.

## *Other concepts*

### Distributed sensor network

If a centralised architecture is used in a sensor network and the central node fails, then the entire network will collapse, however the reliability of the sensor network can be increased by using distributed architecture.
Distributed architecture is used in WSNs for the following reasons:

1. Sensor nodes are prone to failure,
2. For better collection of data
3. To provide nodes with backup in case of failure of the central node

We also take care of nodes sensing redundant information and forwarding the data that is of no use. There is also no centralised body to allocate the resources and they have to be self organised.

### Data visualization

The data gathered from wireless sensor networks is usually saved in the form of numerical data in a central base station. Additionally, the Open Geospatial Consortium (OGC) is specifying standards for interoperability interfaces and metadata encodings that enable real time integration of heterogeneous sensor webs into the Internet, allowing any individual to monitor or control Wireless Sensor Networks through a Web Browser.

### Information fusion

In wireless sensor networks, information fusion, also called data fusion, has been developed for processing sensor data by filtering, aggregating, and making inferences about the gathered data. Information fusion deals with the combination of multiple sources to obtain improved information: cheaper, greater quality or greater relevance. Within the wireless sensor networks domain, simple aggregation techniques such as maximum, minimum, and average, have been developed for reducing the overall data traffic to save energy.