Building Engineering Defects

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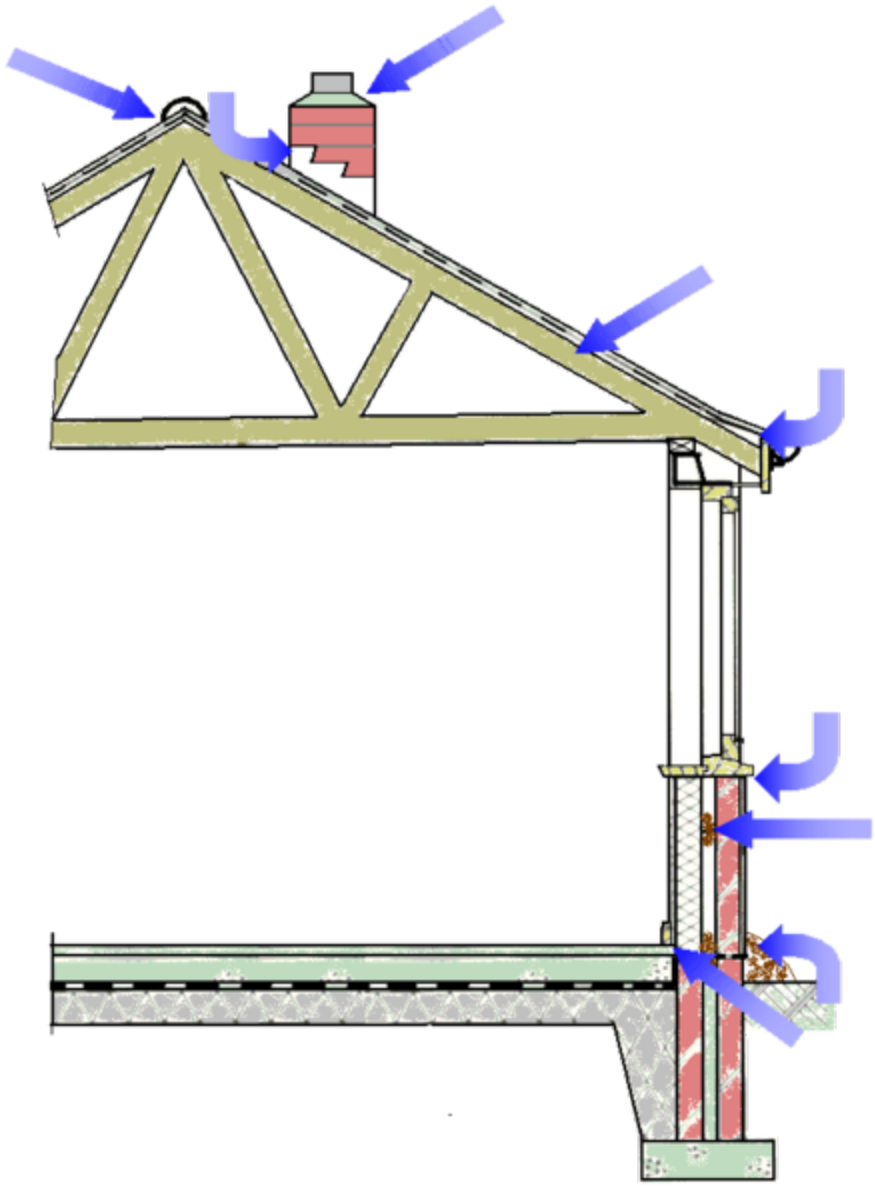
Chapter 1

Damp (Structural)



Detail showing some of the causes of damp penetration

Structural dampness refers to the presence of unwanted moisture in the structure of a building, either the result of intrusion from outside or condensation from within the structure. A high proportion of damp problems in buildings are caused by the "big three," condensation, rain penetration, and rising damp, although other causes of dampness such as pipe leakage and construction moisture should not be overlooked.

Symptoms

Dampness tends to cause secondary damage to a building. The unwanted moisture enables the growth of various fungi in wood, causing rot. Plaster and paint deteriorate and wallpaper loosens. Stains, from the water, salts and from mold, mar surfaces. Externally, mortar may crumble and salt stains may appear on the walls. Steel & iron fasteners rust. It may also cause respiratory illness in occupants. In extreme cases, mortar or plaster may fall away from the affected wall.

A 2009 World Health Organisation report entitled "Children Living in Homes With Problems of Damp" stated that:

"Excess moisture leads – on almost all indoor materials – to growth of microbes such as moulds, fungi and bacteria, which subsequently emit spores, cells, fragments and volatile organic compounds into the indoor air. Moreover, dampness initiates chemical and/or biological degradation of materials, which also causes pollution of the indoor air. Exposure to microbial contaminants is clinically associated with respiratory symptoms, allergies, asthma and immunological reactions. Dampness has therefore been suggested to be a strong and consistent indicator of risk for asthma and respiratory symptoms such as cough and wheeze."

Identification

A wide range of instruments and techniques can be used to investigate the causes of moisture in building materials. When used correctly, they can provide a valuable aid to investigation. The competence and experience of the person undertaking the damp investigations is of greater importance than the kit he or she carries.

Processes for diagnosing rising Damp in buildings is set out in BRE Digest 245.

All of the above should be considered during any assessment for damp related defects in buildings.

Prevention and treatment

Most forms of dampness can be prevented by thoughtful building design and careful construction. In the UK, well built modern houses include a synthetic damp-proof course (DPC), about 15 cm above ground level, to act as a barrier through which water cannot pass. Slate or "engineering bricks" with a low porosity were often used for the first few courses above ground level, and these can in theory help minimise the problem.

There are many approaches to the treatment of dampness in existing buildings. Key to the selection of an appropriate treatment is a correct diagnosis of the types of dampness affecting a building. Details of possible treatments for specific types of dampness are covered in the sections below.

The cause of the dampness must first be eliminated, by providing better drainage or fixing leaking pipes. BRE Digest 245 describes several methods of treating rising damp, including the use of land-drains and the insertion of physical and chemical damp-proof courses. Then, any affected plaster or mortar must be removed, and the wall treated, before replacing the plaster and repainting.

The major damp treatment authorities within the U.K. are The British Wood Preserving and Damp-proofing Association (BWPDA) and The Property Care Association.

Condensation

Condensation comes from water vapour within the building. Common sources may include cooking, bathing etc. The moisture in the air condenses on cold surfaces. Buildings with poorly insulated walls are very prone to this problem. It often causes damage similar to damp in a building and often appears in similar places. This is because it occurs in the "dead air" pockets that accumulate in both horizontal and vertical corners (i.e. out of circulating air patterns).

In the United Kingdom, condensation problems are particularly common between October and March - to the extent that this period is often referred to as the "condensation season."

Identification of condensation

If it is suspected that the problem is condensation, then a room should be sealed off with a dehumidifier left running for the recommended time and then further instrument tests made. If the dampness has disappeared, then condensation is very likely the problem.

Alternatively Humiditect cards or dataloggers (measuring air humidity, air temperature, and surface temperature) can be used as tools for diagnosing a condensation problem.

Treatment

Typical remedies for condensation include increasing background heat and ventilation, improving the insulation of cold surfaces and reducing moisture generation (e.g. by avoiding the drying of clothes indoors).

Rain Penetration

Rain Penetration (also known as "penetrating damp") is a common form of dampness in buildings. It can occur through walls, roofs, or through openings (e.g. window reveals).

Water will often penetrate the outer envelope of a building and appear inside. Common defects include.

- Roof defects such as faulty flashing, cracked or missing slates or tiles.
- Faults in the brickwork or masonry such as missing or cracked pointing. Porous bricks or stones.
- Missing or defective mastic around windows and doors.
- Blocked weep holes.
- Missing or defective trays in cavity walls.

Walls

Rain penetration is most often associated with single-skin walls, but can also occur through cavity walls - e.g. by tracking across wall ties.

Rising dampness

Rising damp is the common term for the slow upward movement of water in the low parts of walls and other ground-supported structures by capillary action. It could be identified by a characteristic "tide mark" on the lower section of affected walls, but this could be caused by damp ingression rather than rising damp. This tide mark is caused by soluble salts (particularly nitrates and chlorides) contained in the groundwater. Due to the effects of evaporation these salts accumulate at the "peak" of the rising damp.

According to Jurin's Law the maximum height of rise is inversely proportional to the capillary radius. Taking a typical pore radius for building materials of 1 μm, Jurin's Law would give a maximum rise of about 15 m, however, due to the effects of evaporation, in practice the rise would be considerably lower.

A "physical model" of rising damp was developed by Christopher Hall and William D Hoff in their paper "Rising damp: capillary rise dynamics in walls". The analysis is based on experimentally well established properties of porous building materials and the physics of evaporation from building surfaces. They state that model can be used to predict the height to which damp will rise in a wall, based on factors such as wall thickness, the sorptivity of the wall structure and the effect of evaporation. Further work has confirmed experimentally the importance of mortar properties in determining the height to which damp will rise in walls. BRE Digest 245 lists several factors that can influence the height of the rise including rate of evaporation from the wall, pore sizes of the masonry, salt content of the materials and the soil, groundwater and degree of saturation, and use of heating within the property. The effect of seasonal variations in evaporation rate on the height of moisture rise have been comprehensively described.

A number of people have expressed the view that rising damp is a myth. A former chairman of the construction arm of the Royal Institution of Chartered Surveyors (RICS), Stephen Boniface, has said that ‘true rising damp’ is a myth and chemically injected damp-proof courses (DPC) are ‘a complete waste of money’. Konrad Fisher's article "The

Fraud of Rising Damp" points out that the historic city hall in Bamberg stands in the river Regnitz and its bridge remains dry without any chemical, mechanical or electronic damp-proof course. In fact, evidence would suggest that not all walls are capable of supporting rising damp, so this finding is not particularly surprising. These views are not reflected by the views the UK Building Research establishment (BRE). Indeed, Part C of the Building Regulations for England and Wales specifically calls for the inclusion of a damp-proof course in all new properties.

A review of data and publications commissioned by the Property Care Association and carried out by the University of Portsmouth concluded that "Rising damp is an age-old and ubiquitous problem." It also noted that "Records on observation and descriptions on this phenomenon date back to early times. It was identified as a public health issue in the second half of the 19th Century."

Diagnosis

The first step in assessing damp is to check for standing water. Removing water with good drainage will remove any form of dampness. Once done, and dampness remains, the next step is to look for the presence of a damp-proof course. If a damp-proof course is present, it is likely to be functioning, as the materials from which damp proof courses are manufactured tend to have a long lifespan. However, it should be acknowledged that there are cases where existing damp proof courses fail for one reason or another.

One method that is often used to determine if the source of dampness is rising damp (rather than other forms of dampness) is to look for the presence of salts - in particular a tell tale "salt band" or "tide mark" at the peak of the damp's rise. Although this is a useful indicator, it is not completely reliable as salts can enter the fabric of the wall in other ways - e.g. unwashed sea sand or gravel used in the construction of the wall.

If there is no damp-proof course and rising damp is suspected (tide mark, moisture confined to lower section of wall etc...) then a number of diagnostic techniques can be used to determine the source of damoness. BRE Digest 245 states that the most satisfactory approach is to obtain samples of mortar in the affected wall using a drill and then analysing these samples do determine their moisture and salt content. The fact that this technique is destructive to the wall finish often makes it unacceptable to homeowners. It is for this reason that electrical moisture meters are often used when surveying for rising damp. These instruments are unable to accurately measure the moisture content of masonry (they were developed for use on timber), however the patterns of readings that they provide can provide a useful indication of the source of dampness.

Treatment

In many cases, damp is caused by "bridging" of a damp-proof course that is otherwise working effectively. For example a flower bed next to an affected wall might result in soil being piled up against the wall above the level of the DPC. In this example, moisture

from the ground would be able to ingress through the wall from the soil. Such a damp problem could be rectified by simply lowering the flower bed to below DPC level.

Where a rising damp problem is caused by a lack of a damp-proof course (common in buildings over approximately 100 years old) or by a failed damp-proof course (comparatively rare) there are a wide range of possible solutions available. These include:

- Replacement physical damp proof course
- Injection of a liquid or cream chemical damp proof course (DPC Injection)
- Porous tubes
- Electrical-osmotic systems
- Land drainage

BRE Digest 245 suggests that with the exception of replacement physical DPCs, only methods of treatment with third party accreditation (E.g. British Board of Agreement Certificate) should be considered. It then goes on to state that the only method of currently satisfying this requirement is DPC injection and that "this is the only method which BRE considers suitable where insertion of a physical DPC is not possible." The Royal Institute of Chartered Surveryors (RICS) publication "Remedying Damp" is more cautious about reliance on third party accredititation, casting doubt upon the validity of the test methods employed, arguing that trials are usually conducted using "specially built masonry panels - which do not match up in many respects to walls found in real properties," and that "if a DPC were proved *to not* work in a specially built masonry panel, this would be the more significant result." The MOAT No 39 test employed by the British Board of Agreement (BBA) in the UK is dismissed as "quite a clever test idea but in the author's opinion not actually replicating a real wall." Furthermore, the point is made that "BBA testing is paid for by manufacturers, and the results are not thought to be publicly available."

Replastering

Replastering will often be carried out as part of a rising damp treatment. Where plaster has become severely damaged by ground salts there is little argument about the need to replaster. However there is considerable debate about:

1. The extent of replastering required
2. The use of hard sand:cement renders to replaster as part of a rising damp treatment

BS6576:2005 states that "the function of the new plaster is to prevent hygroscopic salts that might be present in the wall from migrating through to its surface, while still allowing the wall to dry." However, writing in the RICS publication "Remedying Damp", Ralph Burkinshaw claims that, "the plaster is really there for *two* main reasons." He accepts the need for replastering when significant amounts of ground salts have built up in the existing plaster, however he then goes on to say that replastering is often carried out to make up for an unreliable chemical DPC. He also suggests that damp-proofers

have an incentive to carry out more replastering than is strictly necessary as it allows them to finish the job without having to wait for walls to dry out, resulting in faster payment.

Although the sand:cement renders typically installed as part of a rising damp treatment are very effective at holding back damp and ground salts, they have a number of disadvantages. These include an incompatibility with the soft bricks and mortars encountered in older buildings and a lack of insulation properties compared with more traditional plasters, resulting in an increased risk of condensation. Replastering is also one of the most expensive parts of a rising damp treatment.

Porous renders to German WTA specification 2-2-91 can be used as an alternative to dense sand-cement renders. These have a minimum porosity of 40% of total volume. Salts crystallise in these pores rather than on the plaster surface, avoiding decorative spoiling. Such plasters offer a better solution than dense sand-cement renders when used on moderately salt-contaminated walls as their porous nature gives them insulation properties, resulting in a warmer surface temperature and making condensation problems less likely to occur. However, when used on heavily salt contaminated walls they may need to be replaced frequently as they lose effectiveness once all the pores have become filled with crystallised salt.

Rising Dampness References by Victorians

The issue of rising damp has been a concern since Victorian times. Indeed the Public Heath Act of 1875 introduced the requirement for a damp-proof course in walls to prevent rising damp. An entry in the British medical Journal from 1872 describes the phenomonen as follows:

"Even if the rising damp be arrested by what is technically called an impervious damp-proof course, it will be frequently found that this is built in the wall too near the ground line, so that the heavy rain besplatters the ground and splashes above it. As time rolls on the surface of the ground also becomes elevated, and this damp course is soon lost to sight. Attempts have been made to remedy this evil of porous bricks by the substitution of the hard blue bricks of Staffordshire; and then it may often be noticed that the wet has only struck, sailor-like, across the mortar-joints and chequered the inside walls like a tartan plaid."

The architect, Thomas Worthington, described rising damp in his 1892 essay, "The Dwellings of the Poor: And Weekly Wage-Earners in and Around Towns":

"It should be bourne in mind that damp walls absorb much more heat than dry ones and that they are frequent agents in causing rheumatism, kidney disease and colds. Rising damp from the ground may be prevented by most simple means. Six inches of good Portland cement concrete should cover the whole site of the dwelling, and concrete never less than nine inches thick should underlie all walls. A damp course should disconnect the whole of the foundations from the superstructure. This preventative may consist of a

double layer of thick slates bedded in cement, or of patent perforated stone-ware blocks or of three-quarters of an inch of best asphalt."

Chapter 2

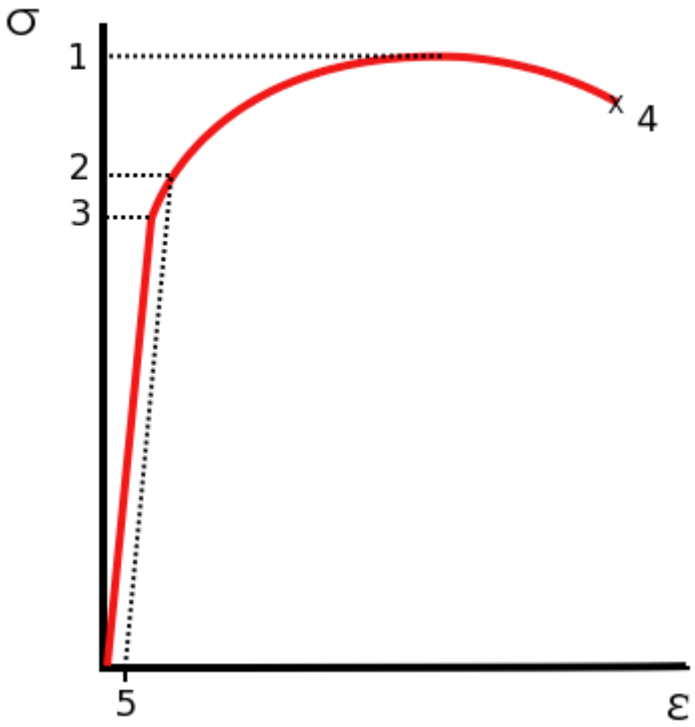
Fracture

A **fracture** is the (local) separation of an object or material into two, or more, pieces under the action of stress.

Sometimes, in crystalline materials, individual crystals fracture without the body actually separating into two or more pieces. Depending on the substance which is fractured, a fracture reduces strength (most substances) or inhibits transmission of light (optical crystals).

A detailed understanding of how fracture occurs in materials may be assisted by the study of fracture mechanics.

Fracture strength



Stress vs. strain curve typical of aluminum
1. Ultimate tensile strength
2. Yield strength
3. Proportional limit stress
4. Fracture
5. Offset strain (typically 0.2%)

Fracture strength, also known as **breaking strength**, is the stress at which a specimen fails via fracture. This is usually determined for a given specimen by a tensile test, which charts the stress-strain curve. The final recorded point is the fracture strength.

Ductile materials have a fracture strength lower than the ultimate tensile strength (UTS), whereas in brittle materials the fracture strength is equivalent to the UTS. If a ductile material reaches its ultimate tensile strength in a load-controlled situation, it will continue to deform, with no additional load application, until it ruptures. However, if the loading is displacement-controlled, the deformation of the material may relieve the load, preventing rupture.

If the stress-strain curve is plotted in terms of *true stress* and *true strain* the curve will always slope upwards and never reverse, as true stress is corrected for the decrease in cross-sectional area. The true stress on the material at the time of rupture is known as the

breaking strength. This is the maximum stress on the true stress-strain curve, given by point 3 on curve B.

Types

Brittle fracture

Brittle fracture in glass.

Fracture of an Aluminum Crank Arm. Bright: Brittle fracture. Dark: Fatigue fracture.

In *brittle fracture*, no apparent plastic deformation takes place before fracture. In brittle crystalline materials, fracture can occur by *cleavage* as the result of tensile stress acting normal to crystallographic planes with low bonding (cleavage planes). In amorphous solids, by contrast, the lack of a crystalline structure results in a conchoidal fracture, with cracks proceeding normal to the applied tension.

The theoretical strength of a crystalline material is (roughly)

$$\sigma_{\text{theoretical}} = \sqrt{\frac{E\gamma}{r_o}}$$

where: -

E is the Young's modulus of the material,

γ is the surface energy, and
r_o is the equilibrium distance between atomic centers.

On the other hand, a crack introduces a stress concentration modeled by

$$\sigma_{\text{elliptical crack}} = \sigma_{\text{applied}}(1 + 2\sqrt{\frac{a}{\rho}}) = 2\sigma_{\text{applied}}\sqrt{\frac{a}{\rho}}$$ (For sharp cracks)

where: -

σ_{applied} is the loading stress,
a is half the length of the crack, and
ρ is the radius of curvature at the crack tip.

Putting these two equations together, we get

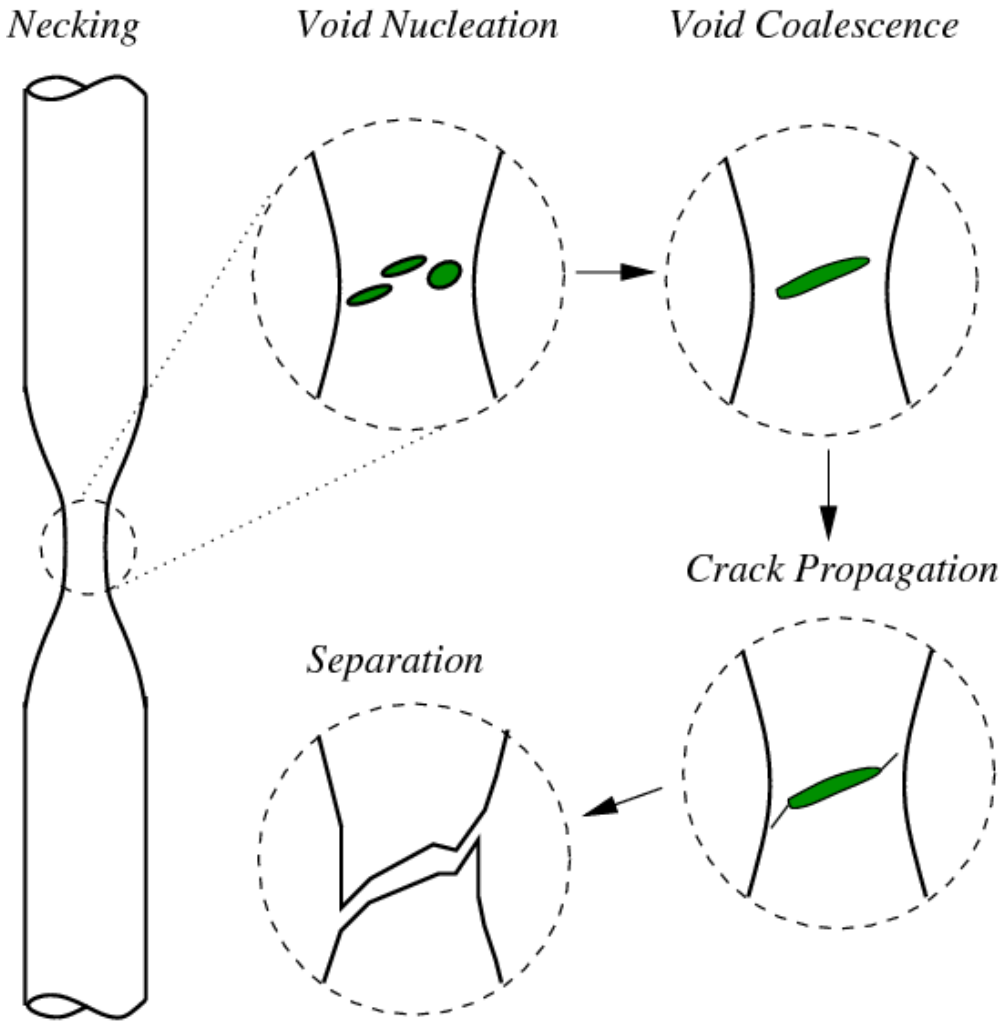
$$\sigma_{\text{fracture}} = \sqrt{\frac{E\gamma\rho}{4ar_o}}.$$

Looking closely, we can see that sharp cracks (small ρ) and large defects (large a) both lower the fracture strength of the material.

Recently, scientists have discovered supersonic fracture, the phenomenon of crack motion faster than the speed of sound in a material. This phenomenon was recently also verified by experiment of fracture in rubber-like materials.

Ductile fracture

Ductile failure of a specimen strained axially.



Schematic representation of the steps in ductile fracture (in pure tension).

In *ductile fracture*, extensive plastic deformation takes place before fracture. The terms *rupture* or *ductile rupture* describe the ultimate failure of tough ductile materials loaded in tension. Rather than cracking, the material "pulls apart," generally leaving a rough surface. In this case there is slow propagation and an absorption of a large amount energy before fracture.

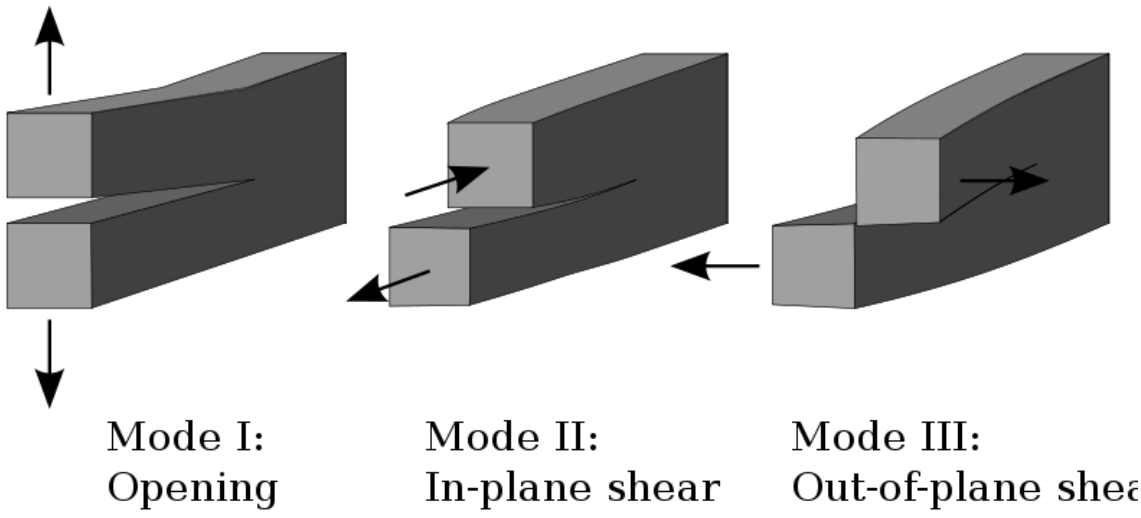
Many ductile metals, especially materials with high purity, can sustain very large deformation of 50–100% or more strain before fracture under favorable loading condition and environmental condition. The strain at which the fracture happens is controlled by the purity of the materials. At room temperature, pure iron can undergo deformation up to 100% strain before breaking, while cast iron or high-carbon steels can barely sustain 3% of strain.

Because ductile rupture involves a high degree of plastic deformation, the fracture behavior of a propagating crack as modeled above changes fundamentally. Some of the

energy from stress concentrations at the crack tips is dissipated by plastic deformation before the crack actually propagates.

The basic steps are: void formation, void coalescence (also known as crack formation), crack propagation, and failure, often resulting in a cup-and-cone shaped failure surface.

Crack separation modes



The three fracture modes.

There are three ways of applying a force to enable a crack to propagate:

- **Mode I crack** – Opening mode (a tensile stress normal to the plane of the crack)
- **Mode II crack** – Sliding mode (a shear stress acting parallel to the plane of the crack and perpendicular to the crack front)
- **Mode III crack** – Tearing mode (a shear stress acting parallel to the plane of the crack and parallel to the crack front)

Chapter 3

Dry Rot

A damaged wall with fruit bodies

Dry rot refers to the decay of timber in buildings and other wooden structures caused by certain fungi. In other fields, the term has also been applied to the decay of crop plants by fungi and the deterioration of rubber. It would appear to be a paradoxical term seemingly indicating decay of a substance without the presence of water. However, its historical usage dates back to the distinction between decay of cured wood in construction, i.e. dry wood, versus decay of wood in living or newly felled trees, i.e. wet wood. In addition, the term can be used as a metaphor for grave underlying problems within a large organization (such as political corruption in government or low morale in the armed forces) that show no symptoms until a sudden, catastrophic failure, much as dry rot of wood in ships caused catastrophic failure.

The term is most commonly used in reference to the decay of building timbers. It refers to damage inflicted by either: *Serpula lacrymans* (formerly *Merulius lacrymans*) predominantly in the United Kingdom and northern Europe; and/or *Meruliporia incrassata* (which has a number of synonyms, including *Poria incrassata* and *Serpula incrassata*) in North America. Both species of fungus cause brown rot decay, preferentially removing cellulose and hemicellulose from the timber leaving a brittle matrix of modified lignin. Eventually the decay can cause instability and collapse in houses, wooden ships' hulls, and other wooden structures.

When applied to these fungi, the term is a somewhat misleading misnomer as both species require an elevated moisture content to initiate an attack on timber (28–30%). Once established, the fungi can remain active in timber with a moisture content of more than 20%. For example, at relative humidities of the surrounding air below 86 percent, growth of *serpula lacrymans* is inhibited, but it can stay dormant at relative humidities down to 76 percent. These relative humidities correspond to equilibrium moisture contents of wood of 19 and 15 percent, respectively.

The perpetual saturation of wood with water inhibits dry rot, as does perpetual dryness.

Historical use of term

‘Dry rot’ is an eighteenth century term for a brown rot. The term was used because the damage was thought to be caused by internal ‘fermentations’ rather than water.

The (London) Times on Tuesday 12 March 1793 carried an advertisement that informs the reader that the British Colour Company, No. 32, Walbrook, London continues to use, manufacture and sell paints prepared with the Oil of Coal, which is of a very penetrating nature, and hardens wood in an uncommon degree protecting it from weather, dry rot and ice.

In the early nineteenth century the rapid increase in instances of timber decay attributed to dry rot (brown rot) in the British naval fleet brought the term into wider usage. Thomas Wade's 'A Treatise on the Dry Rot in Timber' was published posthumously by the Navy Office in 1815 following his investigation of the matter in ships from various countries. The second HMS *Queen Charlotte* was launched in 1810 and, when inspected, the timbers of the upper decks were found to be infected with 'the dry rot'. By 1816 the cost of repairs for this vessel had exceeded the ship's original construction cost.

Texts published in the nineteenth century and early twentieth centuries restrict the term to fungi which produced substantial (white coloured) mycelium including; Antrodia (Fibroporia) vaillantii. Eventually, the term came to apply to only one or two fungi: the main one being Serpula lacrymans', which subsequently became known as 'true dry rot'.

Schilling & Jellison note the potential efficiency of these 'dry rot' fungi in growing away from moisture sources, although there is no reference for how efficient a brown rot fungus has to be at translocating water in order to be classed a 'dry rot' and Schilling

suggests efficient nutrient translocation and utilization, notably nitrogen and iron, may be more distinctive in these species than water translocation. Water translocated in this fashion carries nutrients to the extremities of the organism; not, as is sometimes inferred, to render dry timber wet enough to attack. Coggins goes into more detail about water movement in *S. lacrymans*.

Treatment (of timber decay fungi identified as 'dry rot')

There are epoxy treatments available that kill rot by filling in the channels of the damaged wood, killing the rot and restoring structural integrity. Commercial antifreeze (ethylene glycol) is also very effective at preventing dry rot formation as well as killing the fungus. Certain copper compounds, such as copper naphthenate, are available as a brushable solution and are frequently used when dry-rot damage is repaired by splicing in new wood; after removal of bulk rotten wood the remaining original surface is saturated with such a compound (typically green in color) before application of the new wood.

In certain buildings, particularly those with solid 9 inch (or greater) brickwork and those built using lime mortar and flintstone, dry rot has been known to travel through and along the wall surface behind plaster and render. It is therefore recommended that where dry rot is found, plaster and wall coverings should be stripped back to a metre past the infestation in all directions, and the whole area treated. However, given that dry rot attacks only wet timber, common sense should dictate that plaster need not be removed where there is no timber or any timber is dry (outside the zone of wetting that caused the outbreak). Identifying the source of water and allowing the affected timbers to dry will kill dry rot, as it is a fungus and requires water as all fungi do.

Chapter 4

Dry Rot Treatment

Dry rot treatment refers to the techniques used to eliminate dry rot fungus and alleviate the damage done by the fungus to human-built wooden structures.

The commonly held view of an outbreak of the dry rot fungus (*Serpula lacrymans*) within a building is that it is an extremely serious infestation that is hard to eradicate and requires drastic remedies. The traditional "orthodox" approach to treatment practised by most remedial timber treatment and damp proofing companies accordingly specifies the stripping out of building fabric beyond the visible extent of the infestation and the use of copious amounts of fungicide.

However, new approaches have been gaining ground driven mainly by those with a more scientific understanding of the fungus. The most prominent of which argues that dry rot can be eradicated simply by controlling the environment of the area in which it is growing in terms of reduced moisture levels and increased ventilation.

It is universally accepted that the first priority is to make repairs to rectify the cause of the dampness within the building that allowed the dry rot outbreak to occur in the first place and to promote the drying out of the affected area by taking measures such as increasing ventilation. It is in the way in which the affected building fabric is treated after this that the approaches differ.

Mycology of S. lacrymans

S. lacrymans is a form of brown rot, a group of fungi which digest the cellulose and hemicellulose in timber. This particular species poses the greatest threat to buildings since it can spread through non-nutrient providing materials (e.g., masonry and plaster) for several metres until it finds more timber to attack.

Dry rot is spread by spores which are present in most buildings. The minimum moisture content of timber for spore germination is 28–30% (lower than other rots), and the relative humidity must be in excess of 95%. Spores are resistant to desiccation and may still be viable for germination when they are several years old.

If conditions are suitable, the spore will germinate producing microscopic fungal threads called hyphae.

	Minimum	Optimum	Maximum
Temperature (°C)	−5–+5	15–22	30–40
Timber Moisture Content (%)	22–25	20–55	55–90

Table 1. Environmental conditions for mycelial growth following germination

The average moisture content of modern softwood timbers in dry buildings is generally in the range of 12–15%, and heating systems may reduce this to a far lower level. There is, therefore, no prospect of a dry rot infestation developing in a building that has been properly designed, constructed, and maintained.

Once the environment starts to dry out, the rot will become dormant and eventually die. The length of time that the fungus can remain dormant under dry conditions seems to depend on the temperature, with approximate times of nine years at 7.5 °C and one year at 22 °C being quoted.

Most fungi will only thrive in acid conditions (as found in wood), but dry rot will remain active in alkaline conditions. This gives it the ability to grow through damp mortar, masonry, and plaster and infect other areas of the building. Thick, conducting strands known as rhizomorphs are produced to cross inert surfaces and penetrate masonry.

A fruiting body (sporophore) may develop naturally or in response to unfavourable conditions of humidity, temperature or exhaustion of nutrients. Often the stress that provokes this is the exposure of the infestation. The fruiting body will produce millions of rust brown spores.

One belief held about dry rot is that, once established, it can survive by producing water from the process of breaking down the timber if the original source of water is removed. Laboratory experiments conducted in 1932 on timber samples in unventilated glass jars showed that significant quantities of water were indeed produced. However these experiments do not replicate the “real world” environment of a building where processes of evaporation and capillary action in the wood will be removing moisture from the area faster than it can be produced by the fungus.

Another misconception is that dry rot can transport water from a source over considerable distances to an area of dry timber so that it can start decay there. While the mycelium

strands do conduct a nutrient solution around the fungus it has been shown that any ability to transport water to "wet up" dry timber is very limited.

Despite being a successful coloniser of buildings, for reasons that have not yet been fully explained, *S. lacrymans* is rarely found growing in the wild. Occasional specimens have been found in the foothills of the Indian Himalayas, Mt. Shasta in California, and woodlands in Czechoslovakia.

Treatment Methods

Introduction

The first step in any course of treatment is to make the necessary repairs to the building defects (overflowing gutters, blocked airbricks, missing slates, etc.) that allowed the ingress of dampness. The treatment methods described below assume that the dry rot has been positively identified, the full extent of the ascertained and that the building is now water tight.

A number of methods of attacking dry rot have been developed which can be classified as follows:

- Orthodox – emphasis on the use of chemical fungicides
- Environmental – emphasis on controlling the fungus by controlling environmental conditions
- Heat treatment – exploiting the fungus' sensitivity to heat
- Biological treatment – use of competitor organisms

The latter two methods are included for completeness as they are currently not widely used.

"Orthodox" Treatment for Dry Rot

The following description for the treatment of dry rot is typical of traditional methods:

1. Cut out all wood showing decay, presence of white mycelium, etc. and all apparently sound timber within a radius of one metre of the nearest visibly decayed timber. Burn all such material.
2. Hack off all plaster/render and remove any skirtings, panelling, linings and ceilings necessary to trace the fullest extent of the growth over or through adjacent masonry, concrete or timber surfaces.
3. Clean off with a wire brush all surfaces and any steel and pipe work within the area up to a radius of 1.5 metres from the furthest extent of suspected infection. Remove from the building all dust and debris ensuing from the work.
4. Apply fungicide to all such masonry, concrete and earth surfaces at the specified rate. Apply two generous coats of fungicide to all timber surfaces to a distance of

1.5 metres from the cutting away. (Allow first coat to be absorbed before applying second coat)
5. Use only fully preservative-treated timber for replacement.
6. Replaster with zinc oxychloride (ZOC) plaster or, for areas not to be replastered, apply two coats of ZOC paint.

As can be seen from stages 1 and 2, this involves a removal of a considerable quantity of building fabric.

The desire to kill the fungal strands within all materials adjoining the affected timber has led to the practice of "wall irrigation" at stage 4. This entails saturating the masonry with a water soluble fungicide at a rate of about 10 litres/m^3. Walls of more than half-brick thickness need to be drilled at 230 mm spacing to a depth of just over half the wall thickness. Walls of over 460 mm thickness should be drilled from both sides. Fungicide is then injected into the holes, and the wall faces are sprayed.

Ensuring thorough penetration of fungicide throughout the structure of a non-homogenous wall is extremely difficult. "There is no practical way of ensuring that all dry rot strands within a wall are killed".

A more recent variation of the practice of wall irrigation is the "toxic box" where the area of irrigation is reduced to forming a margin around the perimeter of the wall thereby containing the fungus within the wall. Here it can do no harm and will eventually die for lack of food.

Application of fungicides to the timber at stage 4 may be by brush, spray or injected under pressure into holes drilled into the wood. Preservatives based on organic solvents are used as these have better penetration into wood than water based solutions. Alternatively pastes consisting of a fungicide in an oil/water emulsion may be applied to the timber.

In addition to more conventional fungicides, boron based fungicide can be supplied in glass-like rods which are inserted into holes drilled into the wood. The rods are soluble and should the timber become damp the rod will gradually dissolve diffusing preservative into the damp area. Their use is particularly appropriate for areas that are at risk but not yet affected.

Boron/glycol preservatives consist of an inorganic boron preservative dissolved in a glycol to produce a paste. These are water soluble and will readily diffuse into damp wood, even from the surface, and therefore offer better penetration than more conventional fungicide products, where it is necessary to penetrate damp wood.

"Environmental" Treatment of Dry Rot

The environmental approach can be defined as "the exploitation of the environmental sensitivity of the dry rot fungus for its treatment".

A step-by-step procedure for using the environmental approach would be:

1. Promote the drying out of the affected areas (e.g., by introducing forced ventilation from fans). Do not re-plaster, redecorate or otherwise cover up affected timbers until thoroughly dried out.
2. Identify, with the assistance of a structural engineer where required, any timber that requires replacement or strengthening due to loss of structural strength and carry out these works. Retain as much original fabric as possible, especially in historic buildings.
3. Isolate timbers from other materials that will take a long time to dry out.
4. Increase the ventilation of the area if this is insufficient, by introducing extra air bricks etc.
5. Implement a regular schedule of inspection and maintenance for the building to tackle future problems early on and/or install monitoring equipment.

An example of the situation to which Stage 3 refers would be where a solid stone wall has become soaked due to a gutter becoming blocked and rainwater allowed to overflow down the wall for a period of time. Roof timbers may rest on top of the wall. Even when the ingress of water has been stopped and good ventilation established, it will take a considerable length of time for the wall to dry out. During this time, it is probable that there will be sufficient moisture present to allow fungal growth to continue. In this situation it will be necessary to isolate the timber from the masonry with DPC material. Where the ends of timbers were originally built into a wall and have rotted, these may be cut off flush with the wall and reattached using joist hangers.

Alternatively, the use of pastes and boron rods would be justified in this instance. "Preservative treatments may be essential in some situations if the spread of the fungus is to be restricted and critical timbers are to be protected while the structure dries."

The environmental approach emphasises the need for continued monitoring to ensure that future building defects do not start a new outbreak of dry rot or reactivate a dormant one. While in a simple small building this may be accomplished by regular maintenance inspections, systems are available that can monitor a large building with readings from moisture sensors being remotely monitored by a computer.

Heat Treatment

Other treatments have been tried that attempt to exploit the dry rot's sensitivity to heat. The use of a blowlamp to kill dry rot by applying heat to the surface of affected areas was popular at one time. Obviously, this led to the risk of fire. Experiments showed that a surface temperature of about 1 100 °C would have to be maintained for up to five hours in order to produce a temperature that would be lethal to fungus within a 230 mm thick wall.

In Denmark, a procedure has been developed whereby the building, or the affected part thereof, is tented and heated by hot air to kill dry rot. A temperature of 40 °C is achieved

at the centre of masonry and timbers and maintained for twenty-four hours. However, the question could be asked as to why someone should expend large amounts of energy heating the entire building to a high temperature when all that is needed to kill the rot is to dry it out.

A treatment system using microwaves has also been tried. Further research will be needed before its effectiveness can be assessed.

Biological Control

A further possible way of combating dry rot is by the use of antagonistic organisms that reduce the ability of the decay fungus to colonise or degrade the wood. The principle here is that when in a building the fungus is not in its natural environment and therefore natural competitors are unlikely to be present. It may, however, be possible to introduce these competitors into the building environment to control the dry rot.

Trichoderma fungi remove some structural carbohydrates from the wood necessary for the colonisation and initiation of decay by wood-destroying fungi, and laboratory tests have shown the ability of *Trichoderma* fungi to kill *S. lacrymans*. Field trials have also been carried out investigating the ability of *Trichoderma* fungi to prevent rot in electrical distribution poles, with mixed results.

This sort of biocontrol shows promise in the laboratory but is disappointing in the field, and more work will need to be done. As yet, biological control methods have not become established.

There are also issues with the allergenic potential of *Trichoderma* that may limit its use in situations where human contact is likely.

Criticisms of the Orthodox Approach

Proponents of the environmental approach argue that the drastic action of the orthodox approach is in line with the popular misconception that dry rot is extremely difficult to eradicate. Conversely, they would claim that it is not unusually resilient and is in fact very environmentally sensitive. Indeed, this environmental sensitivity may account for why it is so unsuccessful in the wild and may be used against it when encountered in buildings.

Perhaps the most criticised aspect of the orthodox approach is the practice of wall irrigation. As stated above, this entails introducing large quantities of water-based fungicide into the building fabric. But this is at a time when the primary concern should be to dry the building out.

Excessive water content in the wall will also cause a high risk of the efflorescence of salts out of the wall as it dries thereby damaging plaster and other finishes. Any such salts

deposited on the wall surface may contain the fungicide used in the treatment, thereby creating a potential health hazard.

The ability of irrigation to kill all the fungus within the wall is also questionable, as thorough penetration of the fungicide throughout a non-homogeneous wall is unlikely, resulting in patchy treatment. Case studies have been cited where dry rot has emerged from walls that had previously been "sterilised" by irrigation—in one case, from a wall that had been treated twice before.

It is questionable whether it is necessary to take steps to kill the fungus within the wall at all as the fungal strands are not causing damage to the masonry itself. Instead, they are merely passing through the wall in search of more timber to attack. The "toxic box" technique, as described above, confines the irrigation to the perimeter of the wall. Even the toxic box method has been found to be of limited use. The doubts about complete penetration of any masonry remain, so it is questionable whether a complete barrier of treated material can be formed around the edge of the wall.

The orthodox approach requires that all timbers left in place are protected by the application of a preservative fungicide. As with masonry, it is not easy to achieve full penetration of the timber. The penetration of surface sprays and conventional pastes is severely compromised by high moisture levels in wood. Injection techniques do force fluid within the timber, but distribution throughout the entire piece of wood can be patchy. The use of boron/glycol preservatives do show improved penetration.

Another criticism of the orthodox approach is the sheer amount of building fabric that is removed and the consequent amount of remedial work and disruption to the use of the building. Wall irrigation requires the drilling of a large number of holes into masonry.

Human Health Concerns

One argument put forward by the supporters of the environmental approach concerns the potential effect on human health of the large quantities of toxic chemicals used in orthodox treatments. Typical quotations are: "chemical control methods cause extensive environmental degradation, pose potential hazards to wildlife and are of grave concern to public health bodies" and "…..many cases of illness including headaches, respiratory problems and chest pains, to name a few, have been linked to the use of such agents within buildings. Furthermore, clinical evaluation has tended to validate these concerns."

However, others argue that none of the products used over the last twenty to thirty years have been proven to be harmful to people when properly used. Furthermore, there is a major difference between the use of wood preservatives and pesticides in other situations, especially agriculture, as wood preservatives are put on and into the timber and are designed to stay there for 50 or more years. Pesticides in agriculture, on the other hand, are released into an open environment.

Generally, the toxicity of the fungicides used by the industry has been reduced since 1991 with chemicals such as dieldrin, pentachlorophenol, and tributyltin oxide being replaced by organo-boron esters, permethrin, and boron/glycol mixes. One way of comparing the toxicity of chemicals is by LD_{50}, which gives the dose relative to bodyweight sufficient to kill 50% of the test population (usually rats).

Chemical	Lethal Dose LD50 (mg/kg body weight)
Dieldrin	10
Pentachlorophenol	27
Tributyltin oxide	200
Asprin	1000
Organo-boron esters	1700
Sodium chloride (salt)	3000
Permethrin	4570
Boron/glycol preservatives	8000–15000

Table 2. Relative toxicities of chemicals

Boron-based compounds are toxic to fungi, but their effects on mammals are minimal. However, conventional wood preservatives consist of the active ingredient and a solvent, and it is the organic solvents that seem to give more cause for concern. No ill effects appear to be produced by limited exposure to hydrocarbon solvent vapour, but a higher degree of exposure may cause symptoms such as headaches and nausea, which disappear as soon as exposure ceases.

Some evidence has been produced recently that workers exposed to high levels of solvents over a number of years may develop damage to the central nervous system, but the studies have not been conclusive. This suggests that sufficient ventilation in the treated area until the product is dry is all that is required to prevent any discomfort from the solvent.

Dr. David Watt, in an article published in the *Journal of Nutritional and Environmental Medicine*, is more cautious:

“Chemical treatments used for the control or eradication of fungal infections and/or insect infestations in buildings and the residues of such treatments do not pose a proven hazard to the general population. There is, however, an apparent potential risk from such treatments and from the presence of treatment residues in treated buildings for persons who suffer from chemical sensitivity… it is concluded that further investigation and evaluation is required of alternative chemical and non chemical treatments of fungal infections and/or insect infestations in buildings.”

It should be noted that Watt treats the fungicide as a whole in his article: i.e., he does not separate out the effects of the active ingredients and the solvent.

Environmental Concerns

It has been stated that none of the treatment products used over the last twenty to thirthy years have been proven to have caused any damage to the environment when properly used except in the isolated case of bats. However, in the UK at least, this is a major consideration, as bats are protected under the Wildlife and Countryside Act 1981, which states that harming them or disturbing their roosts is a criminal offence.

Local damage to the environment will result when pesticides are discharged to the ground or rivers due to accident or dumping. Obviously, there is always the possibility that any chemical will not be used correctly, either through ignorance or malice, and the proponents of the environmental approach would argue that there is no need to use large quantities of chemicals anyway when there is a risk, however small.

Effectiveness of Treatments

Experience from companies involved in environmental control and research findings confirm that in most situations dry rot can be fully controlled simply by altering the environment in which it is growing. The Dry Rot Research Group at the University of Abertay have conducted laboratory trials of the environmental control of dry rot on full size models of a floor/wall junction, a window, and a roof/wall junction. The full results are published in a research report by Historic Scotland and conclusively show how the growth of dry rot can be controlled simply by varying the available moisture in the environment.

A case study of successful environmental control of dry rot in a large building is included as an appendix in Historic Scotland's *Technical Advice Note 24*. Case studies are also quoted in Dr. Brian Ridout's book *Timber Decay in Buildings, The Conservation Approach to Treatment*.

Costs

With all treatment methods, the costs of the repairs to rectify the building defects that permitted the ingress of moisture will be the same. The overall cost of using the environmental approach to the treatment of dry rot is likely to be less than the orthodox approach.

Dr. Ridout quotes a case study where an initial quote for orthodox treatment of a building was £23,000 but subsequent treatment by environmental methods resulted in a saving of one third in remedial works and timber replacement. Where it is decided to install moisture monitoring equipment, this will represent a additional capital outlay.

Guarantees

There is a perception amongst the general public that dry rot is difficult to eradicate. It has “instilled fear and dread for centuries”. It is, therefore, not surprising that if a property owner is told that they have such a serious problem, they will expect that drastic action will be required to fix it.

It could be argued that, if a reputable and specialist contractor is employed to administer the orthodox treatment, this has the advantage of coming with the reassurance of a guarantee. Guarantees against the recurrence of dry rot started to be issued in the 1950s, covering treated timbers for a period of 20 years. This period was soon extended to 30 years.

However, the usefulness of the guarantees has been questioned over the inclusion of clauses that exclude liability if the timber is allowed to get wet again during the guarantee period.

An example of the courts enforcing a guarantee is the case of ;;Ackerman v Protim Services;; (1988). In this case, dry rot recurred in a bressummer some eight years after it had been treated for a previous outbreak. The 20-year guarantee issued by the treatment company had a clause that excluded liability if recurrence was due to “a failure to keep the property in a dry and weatherproof condition and in a good and proper state of maintenance”.

The UK Court of Appeal held that the guarantee was not invalidated by this clause because the wall into which the timber was built was damp due to the nature of the construction of the building, not through any lapse in maintenance by the owners. But the clear implication of this is that if the timber had become wet because the property owners had not maintained the building properly, then the guarantee would have become void. In other words, the client is protected against the recurrence of dry rot provided that the conditions that allow dry rot to occur do not recur!

Graham Coleman, a leading specialist in damp treatment and timber decay, makes the same point on his website:

“…But then dry wood doesn't rot - so what is actually being "guaranteed"? Certainly not any chemical treatment that has been applied since it is clearly implied that if treated timber becomes damp it will rot. So what was the value of the preservative treatment? Obviously none!”

Guarantees are therefore of questionable value and may be difficult to enforce. However, the point will still be raised that if the fungicide treatment is really effective, it should not matter whether or not the treated timber gets wet again. If, on the other hand, a fungicide-treated piece of timber must be kept dry to stop it rotting, it cannot be much more resistant to rot than wood that has not been treated.

Some may argue that guarantees for chemical dry rot treatments are, in fact, harmful as they may lure the building owners into a false sense of security by allowing them to feel that they can afford to be less diligent with property maintenance.

Historic Buildings

Richard Oxley of Oxley Conservation states that many remedial timber treatment companies simply do not know enough about the construction of historic buildings to be in a position to advise on appropriate repairs and treatments. He has experience of irreparable damage being done through such lack of knowledge (Oxley, 1995) as does Dr Ridout.

The methods and approaches used to assess and repair timbers in historic buildings have changed considerably in recent years, with a move away from wall irrigation, damage to decorative features during invasive survey work, and unnecessary cutting out or chemical treatment of timbers.

With its emphasis on reducing the amount of building fabric to be removed, the environmental approach obviously has attractions for heritage organisations whose primary purpose is to preserve buildings. Many of these organisations support the environmental approach, for example Dr. Brian Ridout's book *Timber Decay in Buildings, The Conservation Approach to Treatment* being jointly published by English Heritage and Historic Scotland. Historic Scotland's *Technical Advice Note 24* advocates the use of environmental treatment of dry rot, as does advice on the Society for the Preservation of Ancient Building's website.

Chapter 5

Architectural Acoustics

Architectural acoustics is the science of noise control within buildings. The first application of architectural acoustics was in the design of opera houses and then concert halls. More widely, noise suppression is critical in the design of multi-unit dwellings and business premises that generate significant noise, including music venues like bars. The more mundane design of workplaces has implications for noise health effects. Architectural acoustics includes room acoustics, the design of recording and broadcast studios, home theaters, and listening rooms for media playback.

Building skin envelope

This science analyzes noise transmission from building exterior envelope to interior and vice versa. The main noise paths are roofs, eaves, walls, windows, door and penetrations. Sufficient control ensures space functionality and is often required based on building use and local municipal codes. An example would be providing a suitable design for a home which is to be constructed close to a high volume roadway, or under the flight path of a major airport, or of the airport itself.

Inter-space noise control

The science of limiting and/or controlling noise transmission from one building space to another to ensure space functionality and speech privacy. The typical sound paths are room partitions, acoustic ceiling panels (such as wood dropped ceiling panels), doors, windows, flanking, ducting and other penetrations. An example would be providing suitable party wall design in an apartment complex to minimise the mutual disturbance due to noise by residents in adjacent apartments.

Interior space acoustics

This is the science of controlling a room's surfaces based on sound absorbing and reflecting properties. Excessive reverberation time, which can be calculated, can lead to poor speech intelligibility.

Sound reflections create standing waves that produce natural resonances that can be heard as a pleasant sensation or an annoying one. Reflective surfaces can be angled and coordinated to provide good coverage of sound for a listener in a concert hall or music recital space. To illustrate this concept consider the difference between a modern large office meeting room or lecture theater and a traditional classroom with all hard surfaces.

Interior building surfaces can be constructed of many different materials and finishes. Ideal acoustical panels are those without a face or finish material that interferes with the acoustical infill or substrate. Fabric covered panels are one way to heighten acoustical absorption. Finish material is used to cover over the acoustical substrate. Mineral fiber board, or Micore, is a commonly used acoustical substrate. Finish materials often consist of fabric, wood or acoustical tile. Fabric can be wrapped around substrates to create what is referred to as a "pre-fabricated panel" and often provides the good noise absorption if laid onto a wall. Prefabricated panels are limited to the size of the substrate ranging from 2 by 4 feet (0.61 × 1.2 m) to 4 by 10 feet (1.2 × 3.0 m). Fabric retained in a wall-mounted perimeter track system, is referred to as "on-site acoustical wall panels" This is constructed by framing the perimeter track into shape, infilling the acoustical substrate and then stretching and tucking the fabric into the perimeter frame system. On-site wall panels can be constructed to accommodate door frames, baseboard, or any other intrusion. Large panels (generally, greater than 50 square feet or 4.6 square meters) can be created on walls and ceilings with this method. Wood finishes can consist of punched or routed slots and provide a natural look to the interior space, although acoustical absorption may not be great.

There are three ways to improve workplace acoustics and solve workplace sound problems – the ABCs.

- A = Absorb {via drapes, carpets, ceiling tiles, etc.)
- B = Block (via panels, walls, floors, ceilings and layout)
- C = Cover-up (via sound masking)

While all three of these are recommended to achieve optimal results, C = Cover-up by increasing background sound produces the most dramatic improvement in speech privacy – with the least disruption and typically the lowest cost.

Mechanical equipment noise

Building services noise control is the science of controlling noise produced by:

- ACMV (air conditioning and mechanical ventilation) systems in buildings, termed HVAC in North America
- Elevators
- Electrical generators positioned within or attached to a building
- Any other building service infrastructure component that emits sound.

Inadequate control may lead to elevated sound levels within the space which can be annoying and reduce speech intelligibility. Typical improvements are vibration isolation of mechanical equipment, and sound traps in ductwork. Sound masking can also be created by adjusting HVAC noise to a predetermined level.

Chapter 6

Liquid Metal Embrittlement

Liquid metal embrittlement is a phenomenon of practical importance, where certain ductile metals experience drastic loss in tensile ductility or undergo brittle fracture when tested in the presence of specific liquid metals. Generally, a tensile stress, either externally applied or internally present, is needed to induce embrittlement. Exceptions to this rule have been observed, as in the case of aluminium in the presence of liquid gallium. People have studied this phenomenon from the beginning of the 20th century. Many of its phenomenological characteristics are known and several mechanisms were proposed to explain it. The practical significance of liquid metal embrittlement is revealed by the observation that several steels experienced ductility losses and cracking during hot dip galvanizing or during subsequent fabrication.

Liquid metal embrittlement effects can be observed even in solid state, when one of the metals is brought close to its melting point; eg. cadmium-coated parts operating at high temperature.

Characteristics

Mechanical behaviour

Liquid metal embrittlement or LME is characterized by the reduction in the true fracture stress and/or in the strain to fracture when tested in the presence of liquid metals as compared to that obtained in air / vacuum tests. The reduction in fracture strain is generally temperature dependent and a “ductility trough” is observed as the test temperature is decreased. A ductile-to-brittle transition behaviour is also exhibited by many metal couples. The shape of the elastic region of the stress-strain curve is not altered, but the plastic region may be changed during LME. Very high crack propagation rates, varying from few centimeters per second to several meters per second are induced

in solid metals by the embrittling liquid metals. An incubation period and a slow pre-critical crack propagation stage generally precede final fracture.

Metal chemistry

It is believed that there is specificity in the solid-liquid metals combinations experiencing LME. There should be limited mutual solubilities for the metal couple to cause embrittlement. Excess solubility makes sharp crack propagation difficult, but no solubility condition prevents wetting of the solid surfaces by liquid metal and prevents LME. Presence of an oxide layer on the solid metal surface also prevents good contact between the two metals and stops LME. The chemical compositions of the solid and liquid metals affect the severity of embrittlement. Addition of third elements to the liquid metal may increase or decrease the embrittlement and alters the temperature region over which embrittlement is seen. Metal combinations which form intermetallic compounds do not cause LME.

Metallurgy

Alloying of the solid metal alters its LME. Some alloying elements may increase the severity while others may prevent LME. The action of the alloying element is known to be segregation to grain boundaries of the solid metal and altering the grain boundary properties. Accordingly, maximum LME is seen in cases where alloy additions elements have saturated the grain boundaries of the solid metal. The hardness and deformation behaviour of the solid metal affect its susceptibility to LME. Generally harder metals are more severely embrittled. Grain size greatly influences LME. Solids with larger grains are more severely embrittled and the fracture stress varies inversely with the square root of grain diameter. Also the brittle to ductile transition temperature is increased by increasing grain size.

Physico-chemical properties

The interfacial energy between the solid and liquid metals and the grain boundary energy of the solid metal greatly influence LME. These energies depend upon the chemical compositions of the metal couple.

Test parameters

External parameters like temperature, strain rate, stress and time of exposure to the liquid metal prior to testing affect LME. Temperature produces a ductility trough and a ductile to brittle transition behaviour in the solid metal. The temperature range of the trough as well as the transition temperature are altered by the composition of the liquid and solid metals, the structure of the solid metal and other experimental parameters. The lower limit of the ductility trough generally coincides with the melting point of the liquid metal. The upper limit is strain rate sensitive. Temperature also affects the kinetics of LME. An increase in strain rate increases the upper limit temperature as well as the crack

propagation rate. In most metal couples LME does not occur below a threshold stress level.

Mechanisms

Many theories have been proposed for LME. The major ones are listed below;

- The dissolution-diffusion model of Robertson and Glickman says that adsorption of the liquid metal on the solid metal induces dissolution and inward diffusion. Under stress these processes lead to crack nucleation and propagation.
- The brittle fracture theory of Stoloff and Johnson, Westwood and Kamdar proposed that the adsorption of the liquid metal atoms at the crack tip weakens inter-atomic bonds and propagates the crack.
- Gordon postulated a model based on diffusion-penetration of liquid metal atoms to nucleate cracks which under stress grow to cause failure.
- The ductile failure model of Lynch and Popovich predicted that adsorption of the liquid metal leads to weakening of atomic bonds and nucleation of dislocations which move under stress, pile-up and work harden the solid. Also dissolution helps in the nucleation of voids which grow under stress and cause ductile failure.

All of these models utilize the concept of an adsorption-induced surface energy lowering of the solid metal as the central cause of LME. They succeeded in predicting many of the phenomenological observations. However, a quantitative prediction of LME is still elusive.

Mercury embrittlement

The most common liquid metal causing embrittlement is mercury. Its spills present especially significant danger for airplanes. The aluminium-zinc-magnesium-copper alloy DTD 5050B is especially susceptible. The Al-Cu alloy DTD 5020A is less susceptible. Elemental mercury spilled can be immobilized and made relatively harmless by silver nitrate.

On 1 January 2004, the Moomba, South Australia, natural gas processing plant operated by Santos suffered a major fire. The gas release that led to the fire was caused by the failure of a heat exchanger (cold box) inlet nozzle in the liquids recovery plant. The failure of the inlet nozzle was due to liquid metal embrittlement of the train B aluminium cold box by elemental mercury.

Conclusion

Many instances of severe embrittlement of normally ductile materials in the presence of specific liquid metals have been noticed. Numerous investigations on this phenomenon were carried out during the last 100 years resulting in a clear understanding of the phenomenology of the process. A broad understanding of the atomic mechanism of LME also exists. However, a universally applicable theory of the process is yet to evolve.

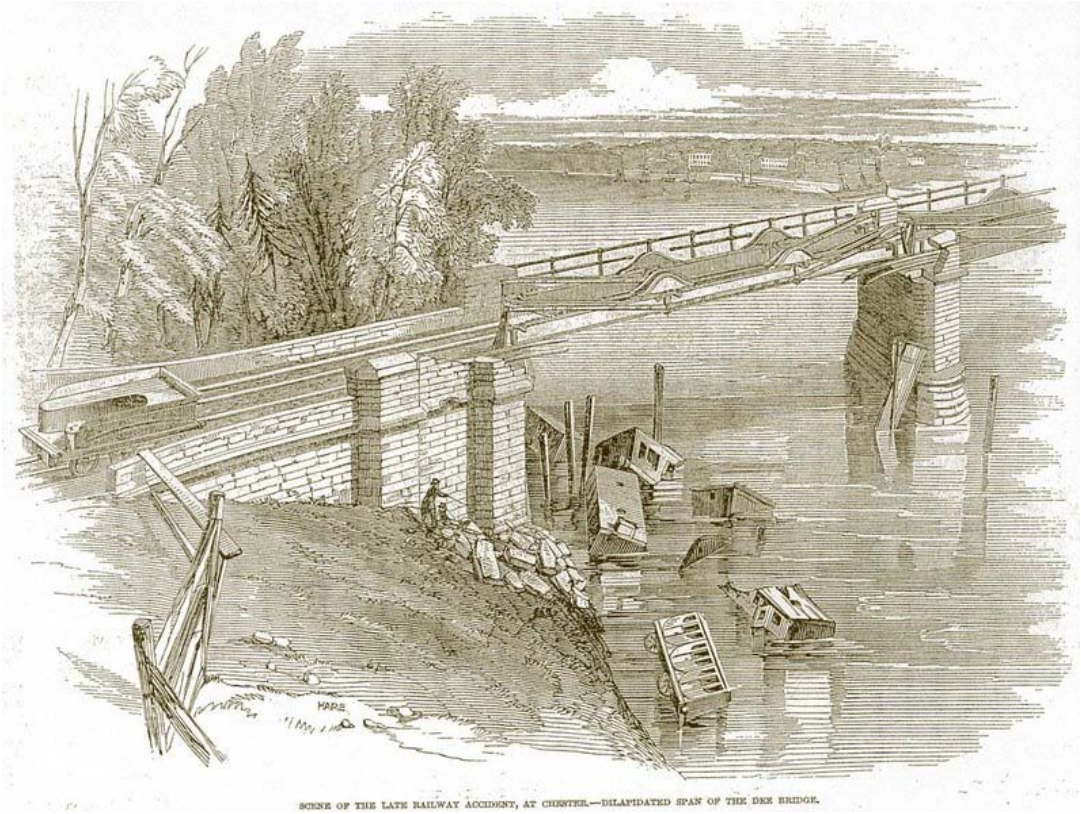
Chapter 7

Structural Failure

Structural failure refers to loss of the load-carrying capacity of a component or member within a structure or of the structure itself. Structural failure is initiated when the material is stressed to its strength limit, thus causing fracture or excessive deformations. In a well-designed system, a localized failure should not cause immediate or even progressive collapse of the entire structure. Ultimate failure strength is one of the limit states that must be accounted for in structural engineering and structural design.

Notable failures

Dee bridge



The Dee bridge after its collapse

On 24 May 1847 the new railway bridge over the river Dee collapsed as a train passed over it, with the loss of 5 lives. It was designed by Robert Stephenson, using cast iron girders reinforced with wrought iron struts. The bridge collapse was the subject of one of the first formal inquiries into a structural failure. The result of the inquiry was that the design of the structure was fundamentally flawed, as the wrought iron did not reinforce the cast iron at all, and due to repeated flexing it suffered a brittle failure due to fatigue.

First Tay Rail Bridge

The Dee bridge disaster was followed by a number of cast iron bridge collapses, including the collapse of the first **Tay Rail Bridge** on 28 December 1879. Like the Dee bridge, the Tay collapsed when a train passed over it causing 75 people to lose their lives. The bridge failed because of poorly made cast iron, and the failure of the designer Thomas Bouch to consider wind loading on the bridge. The collapse resulted in cast iron largely being replaced by steel construction, and a complete redesign in 1890 of the Forth Railway Bridge. As a result, the Forth Bridge was the first entirely steel bridge in the world.

First Tacoma Narrows Bridge

The 1940 collapse of Tacoma Narrows Bridge (1940), as the original Tacoma Narrows Bridge is known, is sometimes characterized in physics textbooks as a classical example of resonance; although, this description is misleading. The catastrophic vibrations that destroyed the bridge were not due to simple mechanical resonance, but to a more complicated oscillation between the bridge and winds passing through it, known as aeroelastic flutter. Robert H. Scanlan, father of the field of bridge aerodynamics, wrote an article about this misunderstanding. This collapse, and the research that followed, led to an increased understanding of wind/structure interactions. Several bridges were altered following the collapse to prevent a similar event occurring again. The only fatality was 'Tubby' the dog.

I-35W Bridge

Security camera images show the I-35W collapse in animation, looking north.

The I-35W Mississippi River bridge (officially known simply as Bridge 9340) was an eight-lane steel truss arch bridge that carried Interstate 35W across the Mississippi River in Minneapolis, Minnesota, United States. The bridge was completed in 1967, and its maintenance was performed by the Minnesota Department of Transportation. The bridge was Minnesota's fifth–busiest, carrying 140,000 vehicles daily. The bridge catastrophically failed during the evening rush hour on 1 August 2007, collapsing to the river and riverbanks beneath. Thirteen people were killed and 145 were injured. Following the collapse The Federal Highway Administration (FHWA)advised states to inspect the 700 U.S. bridges of similar construction after a possible design flaw in the bridge was discovered, related to large steel sheets called gusset plates which were used to connect girders together in the truss structure. Officials expressed concern about many other bridges in the United States sharing the same design and raised questions as to why such a flaw would not have been discovered in over 40 years of inspections.

Buildings

Ronan Point

On 16 May 1968 the 22 storey residential tower Ronan Point in the London Borough of Newham collapsed when a relatively small gas explosion on the 18th floor caused a structural wall panel to be blown away from the building. The tower was constructed of precast concrete, and the failure of the single panel caused one entire corner of the building to collapse. The panel was able to be blown out because there was insufficient reinforcement steel passing between the panels. This also meant that the loads carried by the panel could not be redistributed to other adjacent panels, because there was no route for the forces to follow. As a result of the collapse, building regulations were overhauled to prevent disproportionate collapse and the understanding of precast concrete detailing was greatly advanced. Many similar buildings were altered or demolished as a result of the collapse.

Oklahoma City bombing

On 19 April 1995, the nine story concrete framed Alfred P. Murrah Federal Building in Oklahoma was struck by a huge car bomb causing partial collapse, resulting in the deaths of 168 people. The bomb, though large, caused a significantly disproportionate collapse of the structure. The bomb blew all the glass off the front of the building and completely shattered a ground floor reinforced concrete column. At second story level a wider column spacing existed, and loads from upper story columns were transferred into fewer columns below by girders at second floor level. The removal of one of the lower story columns caused neighbouring columns to fail due to the extra load, eventually leading to the complete collapse of the central portion of the building. The bombing was one of the first to highlight the extreme forces that blast loading from terrorism can exert on buildings, and led to increased consideration of terrorism in structural design of buildings.

9/11

In the September 11 attacks, two commercial airliners were deliberately crashed into the Twin Towers of the World Trade Center in New York City. The impact and resulting fires caused both towers to collapse within two hours. After the impacts had severed exterior columns and damaged core columns, the loads on these columns were redistributed. The hat trusses at the top of each building played a significant role in this redistribution of the loads in the structure. The impacts dislodged some of the fireproofing from the steel, increasing its exposure to the heat of the fires. Temperatures became high enough to weaken the core columns to the point of creep and plastic deformation under the weight of higher floors. Perimeter columns and floors were also weakened by the heat of the fires, causing the floors to sag and exerting an inward force on exterior walls of the building.

Aircraft

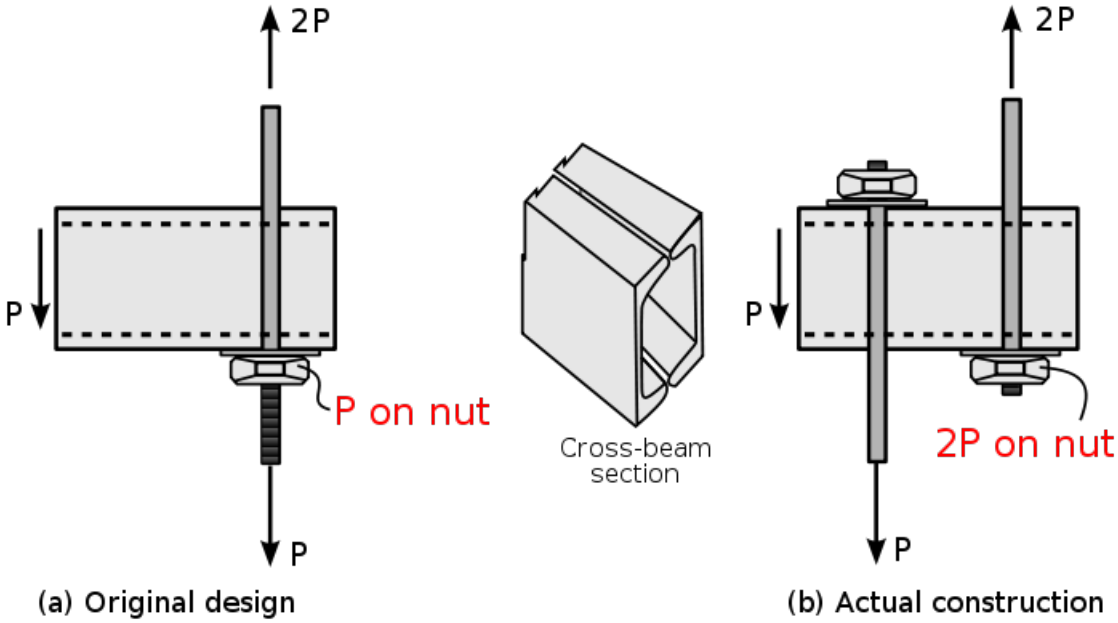
Repeated structural failures of aircraft types occurred in 1954, when 2 de Havilland Comet C1 jet airliners crashed due to decompression caused by metal fatigue, and in 1963-4, when the vertical stabilizer on 4 Boeing B-52 bombers broke off in mid-air.

Other

Warsaw Radio Mast

On 8 August 1991 at 16:00 UTC Warsaw radio mast, the tallest man-made object ever built before the erection of Burj Khalifa collapsed as consequence of an error in exchanging the guy-wires on the highest stock. The mast first bent and then snapped at roughly half its height. It destroyed at its collapse a small mobile crane of Mostostal Zabrze. As all workers left the mast before the exchange procedures, there were no fatalities, in contrast to the similar collapse of WLBT Tower in 1997.

Hyatt Regency walkway



Design change on the Hyatt Regency walkways.

On 17 July 1981, two suspended walkways through the lobby of the Hyatt Regency in Kansas City, Missouri, collapsed, killing 114 and injuring 200 people at a tea dance. The collapse was due to a late change in design, altering the method in which the rods supporting the walkways were connected to them, and inadvertently doubling the forces on the connection. The failure highlighted the need for good communication between design engineers and contractors, and rigorous checks on designs and especially on contractor-proposed design changes. The failure is a standard case study on engineering courses around the world, and is used to teach the importance of ethics in engineering.

Chapter 8

Thermal Expansion

Thermal expansion is the tendency of matter to change in volume in response to a change in temperature.

When a substance is heated, its particles begin moving more and thus usually maintain a greater average separation. Materials which contract with increasing temperature are rare; this effect is limited in size, and only occurs within limited temperature ranges. The degree of expansion divided by the change in temperature is called the material's **coefficient of thermal expansion** and generally varies with temperature.

Overview

Predicting expansion

If an equation of state is available, it can be used to predict the values of the thermal expansion at all the required temperatures and pressures, along with many other state functions.

Contraction effects

A number of materials contract on heating within certain temperature ranges; this is usually called negative thermal expansion, rather than "thermal contraction". For example, the coefficient of thermal expansion of water drops to zero as it is cooled to roughly 4 °C and then becomes negative below this temperature, this means that water has a maximum density at this temperature, and this leads to bodies of water maintaining this temperature at their lower depths during extended periods of sub-zero weather. Also, fairly pure silicon has a negative coefficient of thermal expansion for temperatures between about 18 kelvin and 120 kelvin.

Factors

Unlike gases or liquids, solid materials tend to keep their shape when undergoing thermal expansion.

Thermal expansion generally decreases with increasing bond energy, which also has an effect on the hardness of solids, so, harder materials are more likely to have lower thermal expansion. In general, liquids expand slightly more than solids. The thermal expansion of glasses is higher compared to that of crystals. At the glass transition temperature, rearrangements that occur in an amorphous material lead to characteristic discontinuities of coefficient of thermal expansion or specific heat. These discontinuities allow to detect the glass transition temperature where a supercooled liquid transforms to a glass.

Absorption or desorption of water (or other solvents) can change the size of many common materials; many organic materials change size much more due to this effect than they do to thermal expansion. Common plastics exposed to water can, in the long term, expand many percent.

Coefficient of thermal expansion

The **coefficient of thermal expansion** describes how the size of an object changes with a change in temperature. Specifically, it measures the fractional change in size per degree change in temperature at a constant pressure. Several types of coefficients have been developed: volumetric, area, and linear. Which is used depends on the particular application and which dimensions are considered important. For solids, one might only be concerned with the change along a length, or over some area.

The volumetric thermal expansion coefficient is the most basic thermal expansion coefficient. In general, substances expand or contract when their temperature changes, with expansion or contraction occurring in all directions. Substances that expand at the same rate in every direction are called isotropic. For isotropic materials, the area and linear coefficients may be approximated to good accuracy from a known volumetric coefficient, under some circumstances.

Mathematical definitions of these coefficients are defined below for solids, liquids, and gasses.

General volumetric thermal expansion coefficient

In the general case of a gas, liquid, or solid, the volumetric coefficient of thermal expansion is given by

$$\alpha_V = \frac{1}{V}\left(\frac{\partial V}{\partial T}\right)_p$$

The subscript *p* indicates that the pressure is held constant during the expansion, and the subscript "V" stresses that it is the volumetric (not linear) expansion that enters this general definition. In the case of a gas, the fact that the pressure is held constant is important, because the volume of a gas will vary appreciably with pressure as well as temperature. For a gas of low density this can be seen from the ideal gas law.

Expansion in solids

Materials generally change their size when subjected to a temperature change while the pressure is held constant. In the special case of solid materials, the pressure does not appreciably affect the size of an object, and so for solids, it's usually not necessary to specify that the pressure be held constant.

Common engineering solids usually have coefficients of thermal expansion that do not vary significantly over the range of temperatures where they are designed to be used, so where extremely high accuracy is not required, practical calculations can be based on a constant, average, value of the coefficient of expansion.

Linear expansion

The linear thermal expansion coefficient relates the change in a material's linear dimensions to a change in temperature. It is the fractional change in length per degree of temperature change. Ignoring pressure, we may write:

$$\alpha_L = \frac{1}{L}\frac{dL}{dT}$$

where L is the linear dimension (e.g. length) and dL / dT is the rate of change of that linear dimension per unit change in temperature.

The change in the linear dimension can be estimated to be:

$$\frac{\Delta L}{L} = \alpha_L \Delta T$$

This equation works well as long as the linear expansion coefficient does not change much over the change in temperature ΔT. If it does, the equation must be integrated.

Effects on strain

For solid materials with a significant length, like rods or cables, an estimate of the amount of thermal expansion can be described by the material strain, given by $\epsilon_{thermal}$ and defined as:

$$\epsilon_{thermal} = \frac{(L_{final} - L_{initial})}{L_{initial}}$$

where $L_{initial}$is the length before the change of temperature and $L_{final}$is the length after the change of temperature.

For most solids, thermal expansion relates directly with temperature:

$$\epsilon_{thermal} \propto \Delta T$$

Thus, the change in either the strain or temperature can be estimated by:

$$\epsilon_{thermal} = \alpha_L \Delta T$$

where

$$\Delta T = (T_{final} - T_{initial})$$

is the difference of the temperature between the two recorded strains, measured in degrees Celsius or kelvins, and $\alpha_L$is the linear coefficient of thermal expansion in *inverse kelvins*.

Area expansion

The area thermal expansion coefficient relates the change in a material's area dimensions to a change in temperature. It is the fractional change in area per degree of temperature change. Ignoring pressure, we may write:

$$\alpha_A = \frac{1}{A}\frac{dA}{dT}$$

where *A* is some area of interest on the object, and *dA* / *dT* is the rate of change of that area per unit change in temperature.

The change in the linear dimension can be estimated as:

$$\frac{\Delta A}{A} = \alpha_A \Delta T$$

This equation works well as long as the linear expansion coefficient does not change much over the change in temperature δ*T*. If it does, the equation must be integrated.

Volumetric expansion

For a solid, we can ignore the effects of pressure on the material, and the volumetric thermal expansion coefficient can be written :

$$\alpha_V = \frac{1}{V}\frac{dV}{dT}$$

where V is the volume of the material, and dV / dT is the rate of change of that volume with temperature.

This means that the volume of a material changes by some fixed fractional amount. For example, a steel block with a volume of 1 cubic meter might expand to 1.002 cubic meters when the temperature is raised by 50 °C. This is an expansion of 0.2%. If we had a block of steel with a volume of 2 cubic meters, then under the same conditions, it would expand to 2.004 cubic meters, again an expansion of 0.2%. The volumetric expansion coefficient would be 0.2% for 50 °C, or 0.004% per degree C.

If we already know the expansion coefficient, then we can calculate the change in volume

$$\frac{\Delta V}{V} = \alpha_V \Delta T$$

where ΔV / V is the fractional change in volume (e.g., 0.002) and ΔT is the change in temperature (50 C).

The above example assumes that the expansion coefficient did not change as the temperature changed. This is not always true, but for small changes in temperature, it is a good approximation. If the volumetric expansion coefficient does change appreciably with temperature, then the above equation will have to be integrated:

$$\frac{\Delta V}{V} = \int_{T_0}^{T_0+50} \alpha_V(T)\, dT$$

where T_0 is the starting temperature and $\alpha_V(T)$ is the volumetric expansion coefficient as a function of temperature T.

Isotropic materials

For exactly isotropic materials, and for small expansions, the linear thermal expansion coefficient is almost exactly one third the volumetric coefficient.

$$\alpha_V \approx 3\alpha_L$$

This ratio arises because volume is composed of three mutually orthogonal directions. Thus, in an isotropic material, one-third of the volumetric expansion is in a single axis (a very close approximation for small differential changes). As an example, take a cube of steel that has sides of length L. The original volume will be $V = L^3$ and the new volume, after a temperature increase, will be

$$V+\Delta V = (L+\Delta L)^3 = L^3+3L^2\Delta L+3L\Delta L^2+\Delta L^3 \approx L^3+3L^2\Delta L = V+3V\frac{\Delta L}{L}$$

We can make the substitutions $\Delta V = \alpha_V L^3 \Delta T$ and, for isotropic materials, $\Delta L = \alpha_L L \Delta T$. We now have:

$$L^3 + L^3\alpha_V\Delta T = L^3 + 3L^3\alpha_L\Delta T + 3L^3\alpha_L^2\Delta T^2 + L^3\alpha_L^3\Delta T^3 \approx L^3 + 3L^3\alpha_L\Delta T$$

Since the volumetric and linear coefficients are defined only for extremely small temperature and dimensional changes, the last two terms can be ignored and we get the above relationship between the two coefficients. If we are trying to go back and forth between volumetric and linear coefficients using larger values of ΔT then we will need to take into account the third term, and sometimes even the fourth term.

Similarly, the area thermal expansion coefficient is 2/3 of the volumetric coefficient.

$$\alpha_A = \tfrac{2}{3}\alpha_V$$

This ratio can be found in a way similar to that in the linear example above, noting that the area of a face on the cube is just L^2. Also, the same considerations must be made when dealing with large values of ΔT

Anisotropic materials

Materials with anisotropic structures, such as crystals and many composites, will generally have different linear expansion coefficients α_L in different directions. As a result, the total volumetric expansion is distributed unequally among the three axes. If the crystal symmetry is monoclinic or triclinic even the angles between these axes are subject to thermal changes. In such cases it is necessary to treat thermal expansion as a tensor that has up to six independent elements. A good way to determine the elements of the tensor is to study the expansion by powder diffraction.

Expansion in gases

For an ideal gas, the volumetric thermal expansivity (i.e. relative change in volume due to temperature change) depends on the type of process in which temperature is changed. Two known cases are isobaric change, where pressure is held constant, and adiabatic change, where no work is done and no change in entropy occurs.

In an isobaric process, the volumetric thermal expansivity, which we denote β_p, is:

$$PV = nRT$$
$$\ln(V) = \ln(T) + \ln(nR/P)$$
$$\beta_p = \left(\frac{1}{V}\frac{dV}{dT}\right)_p = \left(\frac{d(lnV)}{dT}\right)_p = \frac{d(lnT)}{dT} = \frac{1}{T}$$

The index *p* denotes an isobaric process.

Expansion in liquids

Theoretically, the coefficient of linear expansion can be approximated from the coefficient of volumetric expansion ($\beta \approx 3\alpha$). However, for liquids, α is calculated through the experimental determination of β.

Examples and Applications

The expansion and contraction of materials must be considered when designing large structures, when using tape or chain to measure distances for land surveys, when designing molds for casting hot material, and in other engineering applications when large changes in dimension due to temperature are expected.

Thermal expansion is also used in mechanical applications to fit parts over one another, e.g. a bushing can be fitted over a shaft by making its inner diameter slightly smaller than the diameter of the shaft, then heating it until it fits over the shaft, and allowing it to cool after it has been pushed over the shaft, thus achieving a 'shrink fit'. Induction shrink fitting is a common industrial method to pre-heat metal components between 150 °C and 300 °C thereby causing them to expand and allow for the insertion or removal of another component.

There exist some alloys with a very small linear expansion coefficient, used in applications that demand very small changes in physical dimension over a range of temperatures. One of these is Invar 36, with α approximately equal to 0.6×10^{-6}/°C. These alloys are useful in aerospace applications where wide temperature swings may occur.

Pullinger's apparatus is used to determine linear expansion of a metallic rod in laboratory. The apparatus consists of a metal cylinder closed at both ends (called a steam jacket). It is provided with an inlet and outlet for the steam. The steam for heating the rod is supplied by a boiler which is connected by a rubber tube to the inlet. The center of cylinder contains a hole to insert a thermometer. The rod, under investigation, is enclosed in a steam jacket. Its one end is free, but the second end is pressed against a fixed screw. The position of the rod is determined by a micrometer screw gauge or spherometer.

The control of thermal expansion in ceramics is a key concern for a wide range of reasons. For example, ceramics are brittle and cannot tolerate sudden changes in

temperature (without cracking) if their expansion is too high. Ceramics need to be joined or work in consort with a wide range of materials and therefore their expansion must be matched to the application. Because glazes need to be firmly attached to the underlying porcelain (or other body type) their thermal expansion must be tuned to 'fit' the body so that crazing or shivering do not occur. Good example of products whose thermal expansion is the key to their success are CorningWare and the spark plug. The thermal expansion of ceramic bodies can be controlled by firing to create crystalline species that will influence the overall expansion of the material in the desired direction. In addition or instead the formulation of the body can employ materials delivering particles of the desired expansion to the matrix. The thermal expansion of glazes is controlled by their ceramic chemistry. In most cases there are complex issues involved in controlling body and glaze expansion, adjusting for thermal expansion must be done with an eye to other properties that will be affected, generally trade-offs are required.

Heat-induced expansion has to be taken into account in most areas of engineering. A few examples are:

- Metal framed windows need rubber spacers
- Rubber tires
- Metal hot water heating pipes should not be used in long straight lengths
- Large structures such as railways and bridges need expansion joints in the structures to avoid sun kink
- One of the reasons for the poor performance of cold car engines is that parts have inefficiently large spacings until the normal operating temperature is achieved.
- A gridiron pendulum uses an arrangement of different metals to maintain a more temperature stable pendulum length.
- A power line on a hot day is droopy, but on a cold day it is tight. This is because the metals expand under heat.

Thermometers are another application of thermal expansion — most contain a liquid (usually mercury or alcohol) which is constrained to flow in only one direction (along the tube) due to changes in volume brought about by changes in temperature. A bi-metal mechanical thermometer uses a bimetallic strip and registers changes due to the differing coefficient of thermal expansion between the two materials.

Thermal expansion coefficients for various materials

This section summarizes the coefficients for some common materials.

In the table below, the range for α is from 10^{-7}/°C for hard solids to 10^{-3}/°C for organic liquids. α varies with the temperature and some materials have a very high variation.

Theoretically, the coefficient of linear expansion can be approximated from the coefficient of volumetric expansion ($\beta \approx 3\alpha$). However, for liquids, α is calculated through the experimental determination of β, so it is more accurate to state β here, rather than α.

(The formula $\beta \approx 3\alpha$ is usually used for solids.)

Material	Linear coefficient, α, at 20 °C (10^{-6}/°C)	Volumetric coefficient, β, at 20 °C (10^{-6}/°C)	Notes
Aluminium	23	69	
Benzocyclobutene	42	126	
Brass	19	57	
Carbon steel	10.8	32.4	
Concrete	12	36	
Copper	17	51	
Diamond	1	3	
Ethanol	250	750	Linear value is approximate
Gallium(III) arsenide	5.8	17.4	
Gasoline	317	950	Linear value is approximate
Glass	8.5	25.5	
Glass, borosilicate	3.3	9.9	
Gold	14	42	
Indium phosphide	4.6	13.8	
Invar	1.2	3.6	
Iron	11.1	33.3	
Lead	29	87	
MACOR	9.3		
Magnesium	26	78	
Mercury	61	182	Linear value is approximate
Molybdenum	4.8	14.4	
Nickel	13	39	
Oak	54	162	Perpendicular to the grain
Pine	34	102	Perpendicular to the grain
Platinum	9	27	
PVC	52	156	
Quartz (fused)	0.59	1.77	
Rubber	77	231	
Sapphire	5.3		Parallel to C axis, or

			[001]
Silicon Carbide	2.77	8.31	
Silicon	3	9	
Silver	18	54	
Sitall	0.15	0.45	
Stainless steel	17.3	51.9	
Steel	11.0 ~ 13.0	33.0 ~ 39.0	Depends on composition
Tungsten	4.5	13.5	
Water	69	207	Linear value is approximate
YbGaGe	0	0	

Chapter 9

Piping and Plumbing Fittings

Fittings are used in pipe and plumbing systems to connect straight pipe or tubing sections, to adapt to different sizes or shapes, and to regulate fluid flow, for example. Fittings, especially uncommon types, can be expensive, and require time, materials, and tools to install, so they are a non-trivial part of piping and plumbing systems. Valves are technically fittings, but are usually discussed separately.

Materials

The bodies of fittings for pipe and tubing are most often of the same base material as the pipe or tubing being connected, for example, copper, steel, brass, polyvinyl chloride (PVC), or chlorinated polyvinyl chloride (CPVC). However, any material that is allowed by code may be used, but must be compatible with the other materials in the system, the fluids being transported, and the temperatures and pressures inside and outside of the system. For example, brass-bodied fittings are common in otherwise copper piping and plumbing systems. Fire hazards, earthquakes, and other factors also influence fitting materials.

Common fittings for both piping and plumbing

While there are hundreds of specialized fittings manufactured, some fittings are used widely in piping and plumbing systems.

Elbow

A pipe fitting installed between two lengths of pipe or tube allowing a change of direction, usually 90° or 45°. The ends may be machined for butt welding, threaded (usually female), or socketed, etc. When the two ends differ in size, it is called a reducing or reducer elbow.

Most elbows are available in short radius or long radius of types. The short radius elbows have a center to end distance equal to the Nominal Pipe Size (NPS) in inches, while the long radius is 1.5 times the NPS in inches. Short elbows are universally available; long elbows are readily available in acrylonitrile butadiene styrene (ABS, plastic), polyvinyl chloride (PVC) for DWV, sewage and central vacuums, chlorinated polyvinyl chloride (CPVC) and copper for 1950s to 1960s houses with copper drains.

Reducer

A reducer allows for a change in pipe size to meet hydraulic requirements of the system or to adapt to existing piping of a different size. Reducers are usually concentric but eccentric reducers are used when required to maintain the same top- or bottom-of-pipe level.

Tee

A tee is used to either combine or split a fluid flow. Most common are tees with the same inlet and outlet sizes, but 'reducing' tees are available as well.

Cross

A cross has one inlet and three outlets, or vice versa. Crosses are common in fire sprinkler systems, but not in plumbing due to their extra cost as compared to using two tees.

The three outlets should be named in order; left, middle , right. For example 15-22-15

Cap

A type of pipe fitting, often liquid or gas tight, which covers the end of a pipe. A cap has a similar function to a plug. In plumbing systems that use threads the cap has female threads.

Plug

A plug closes off the end of a pipe. It is similar to a cap but it fits inside the fitting it is mated to. In a threaded iron pipe plumbing system, plugs have male threads.

Nipple

Short stub of pipe, usually threaded iron, brass, chlorinated polyvinyl chloride (CPVC) or copper; occasionally just bare copper. A nipple is defined as being a short stub of pipe which has two male ends. Nipple are commonly used for plumbing and hoses, and second as valves for funnels and pipes.

Barb

A barb is used to connect flexible hoses to pipes. One end has a stub with ridges which is inserted into the flexible hose to secure it.

Additional common fittings for plumbing systems

Closet flange

The closet flange is the drain pipe flange to which a 'water closet' (toilet) is attached.

Clean-outs

Clean-outs are fittings that allow access to drains without removing plumbing fixtures. They are used for allowing an 'auger' or 'plumber's snake' to 'clean out' a plugged drain. Clean-outs should be placed in accessible locations throughout a drainage system, and outside the building as these augers have limited length. The minimum is typically at the end of each branch, just ahead of each water closet, at the base of each stack, and both inside and outside the building in the building drain/sewer. Clean-outs normally have screw-on caps. Clean-outs are also known as 'rodding eyes' from the eye-shaped cover plates used on external versions.

Trap primers

Trap primers regularly inject water into traps so that *water seals* are maintained. This seal is necessary to keep sewer gases out of buildings. The trap primer must also be in a readily available place for easy access for adjustments, replacement, and or repair.

Combo-Tee

A combination tee (combo tee) is a tee with a gradually curving center connecting joint. It's used in drain systems to provide a smooth, gradually curving path to reduce the likelihood of clogs and to ease pushing a plumber's snake through a drain system. The "combo" is a combination of a wye and a 1/8 bend or 45° elbow.

Sanitary Tee

A sanitary tee is a tee with a curved center section designed to minimize the possibility of siphon action that could draw water out of a trap. The center connection is generally connected to the pipe which leads to a trap (the trap arm).

Double Sanitary Tee (Sanitary Cross)

Similar to a cross. This fitting differs from a standard cross in that two of the ports have curved inlets. The fitting has been used in the past for connecting the drains of back to back fixtures (such as back to back bathroom sinks). Some current codes (including the 2006 UPC) preclude the use of this fitting for that purpose. Instead a Double Fixture Fitting is required.

Wye fitting

A type of waste fitting tee which has the side inlet pipe entering at a 45° angle.

Double-tapped bushing

A double-tapped bushing is a fitting that has opposing threads on the inside diameter of the bushing.

Hydraulic fittings

Hydraulics use extremely high fluid pressures to create useful work, such as in the actuators for machinery such as backhoes. As such the hydraulic fittings are designed and rated for much greater pressures than those experienced in general piping systems and they are generally not compatible for use in general plumbing. More information on hydraulics and their fittings can be found in the hydraulic machinery article.

Types of Connections

Threaded Pipe

A threaded pipe is a pipe with a screw thread at one or both ends for assembly. With a screw thread at one end, the other end may be welded.

Coupling

A coupling connects two pipes to each other. If the size of the pipe is not the same , the fitting may be called a 'reducing coupling' or **reducer**, or an **adapter**. The term 'expander' is not used for a coupler that increases pipe size; instead 'reducer' is used.

Union

A union is similar to a coupling, except it is designed to allow quick and convenient disconnection of pipes for maintenance or fixture replacement. While a coupling would require either solvent welding, soldering or being able to rotate with all the pipes adjacent as with a threaded coupling, a union provides a simple nut transition, allowing easy release at any time.

In addition to a standard union, there exist dielectric unions which are used to separate dissimilar metals (such as copper and galvanized steel) to avoid the damaging effects of galvanic corrosion. When two dissimilar metals are placed in an electrically conductive solution (even tap water is conductive), they will form a battery and generate a voltage by electrolysis. When the two metals are in contact with each other the current from one metal to the other will cause a movement of ions from one to the other, dissolving one metal and depositing it on the other. A dielectric union breaks the electric current with a plastic liner between two halves of the union, thus limiting galvanic corrosion.

Solvent Welding

A solvent is applied to PVC piping that dissolves and fuses the adjacent surfaces of piping. This is used with a sleeve-type joint.

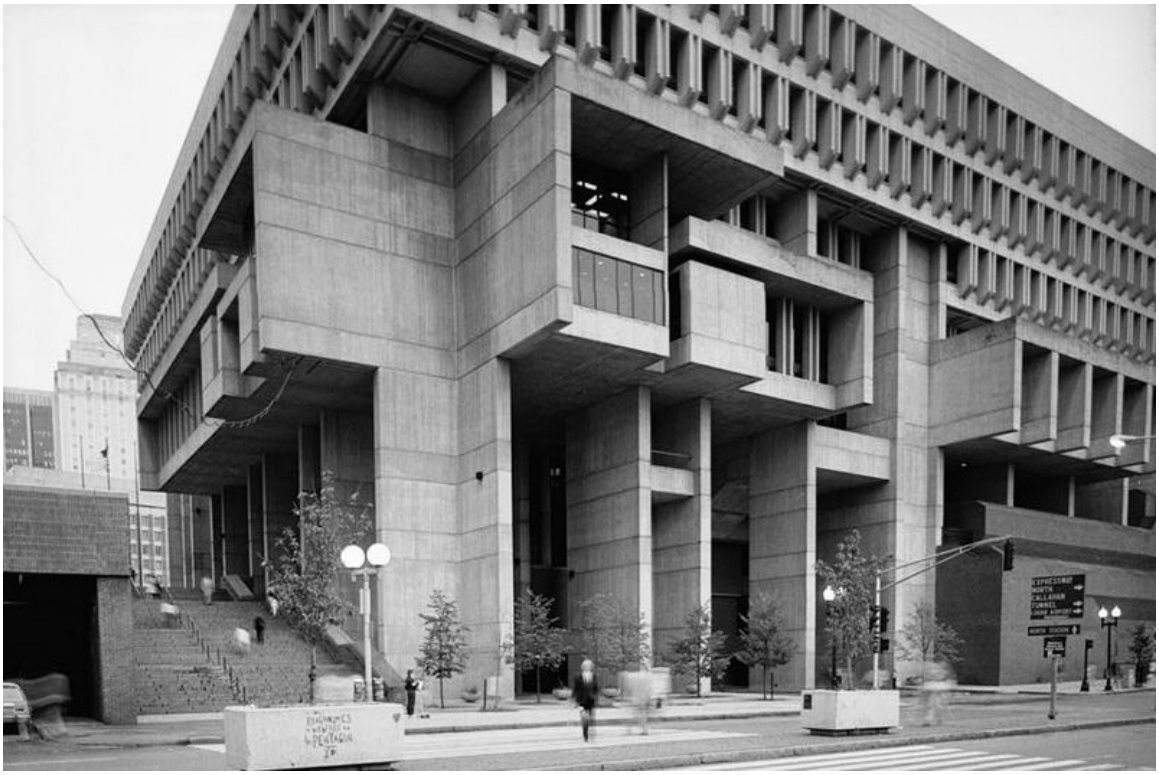
Soldering

Flux is applied to the inner sleeve of a sleeve type joint. The joint is then heated using a propane or MAPP gas torch, solder is applied to the heated joint, and the solder is drawn into the joint as the flux vaporizes.

Chapter 10

Concrete

Outer view of the Roman Pantheon, still the largest unreinforced solid concrete dome.



A modern building: Boston City Hall (completed 1968) is largely constructed of concrete, both pre-cast and poured-in-place.

Opus caementicium laying bare on a tomb near Rome. In contrast to modern concrete structures, the concrete walls of Roman buildings were covered, usually with brick or stone.

Hennebique House in Bourg-la-Reine, constructed between 1894 and 1904, the first concrete building in France.

Concrete is a composite construction material, composed of cement (commonly Portland cement) and other cementitious materials such as fly ash and slag cement, aggregate (generally a coarse aggregate made of gravels or crushed rocks such as limestone, or granite, plus a fine aggregate such as sand), water, and chemical admixtures.

The word concrete comes from the Latin word "concretus" (meaning compact or condensed), the perfect passive participle of "concresco", from "com-" (together) and "cresco" (to grow).

Concrete solidifies and hardens after mixing with water and placement due to a chemical process known as hydration. The water reacts with the cement, which bonds the other components together, eventually creating a robust stone-like material. Concrete is used to make pavements, pipe, architectural structures, foundations, motorways/roads, bridges/overpasses, parking structures, brick/block walls and footings for gates, fences and poles.

Concrete is used more than any other man-made material in the world. As of 2006, about 7.5 cubic kilometres of concrete are made each year—more than one cubic metre for every person on Earth.

Concrete powers a US$35 billion industry, employing more than two million workers in the United States alone. More than 55,000 miles (89,000 km) of highways in the United States are paved with this material. Reinforced concrete, prestressed concrete and precast concrete are the most widely used types of concrete functional extensions in modern days.

History

Concrete has been used for construction in various ancient civilizations. An analysis of ancient Egyptian pyramids has shown that concrete may have been employed in their construction.

During the Roman Empire, Roman concrete (or *opus caementicium*) was made from quicklime, pozzolana, and an aggregate of pumice. Its widespread use in many Roman structures, a key event in the history of architecture termed the Roman Architectural Revolution, freed Roman construction from the restrictions of stone and brick material and allowed for revolutionary new designs both in terms of structural complexity and dimension.

Hadrian's Pantheon in Rome is an example of Roman concrete construction.

Concrete, as the Romans knew it, was a new and revolutionary material. Laid in the shape of arches, vaults and domes, it quickly hardened into a rigid mass, free from many of the internal thrusts and strains that trouble the builders of similar structures in stone or brick.

Modern tests show that *opus caementicium* had as much compressive strength as modern Portland-cement concrete (ca. 200 kg/cm^2). However, due to the absence of steel reinforcement, its tensile strength was far lower and its mode of application was also different:

Modern structural concrete differs from Roman concrete in two important details. First, its mix consistency is fluid and homogeneous, allowing it to be poured into forms rather than requiring hand-layering together with the placement of aggregate, which, in Roman practice, often consisted of rubble. Second, integral reinforcing steel gives modern concrete assemblies great strength in tension, whereas Roman concrete could depend only upon the strength of the concrete bonding to resist tension.

The widespread use of concrete in many Roman structures has ensured that many survive to the present day. The Baths of Caracalla in Rome are just one example. Many Roman

aqueducts and bridges have masonry cladding on a concrete core, as does the dome of the Pantheon.

Some have stated that the secret of concrete was lost for 13 centuries until 1756, when the British engineer John Smeaton pioneered the use of hydraulic lime in concrete, using pebbles and powdered brick as aggregate. However, the Canal du Midi was built using concrete in 1670. Likewise there are concrete structures in Finland that date back to the 16th century. Portland cement was first used in concrete in the early 1840s.

Additives

Concrete additives have been used since Roman and Egyptian times, when it was discovered that adding volcanic ash to the mix allowed it to set under water. Similarly, the Romans knew that adding horse hair made concrete less liable to crack while it hardened, and adding blood made it more frost-resistant.

Recently, the use of recycled materials as concrete ingredients has been gaining popularity because of increasingly stringent environmental legislation. The most conspicuous of these is fly ash, a by-product of coal-fired power plants. This significantly reduces the amount of quarrying and landfill space required, and, as it acts as a cement replacement, reduces the amount of cement required.

In modern times, researchers have experimented with the addition of other materials to create concrete with improved properties, such as higher strength or electrical conductivity. Marconite is one example.

Composition

There are many types of concrete available, created by varying the proportions of the main ingredients below. By varying the proportions of materials, or by substitution for the cemetitious and aggregate phases, the finished product can be tailored to its application with varying strength, density, or chemical and thermal resistance properties.

The *mix design* depends on the type of structure being built, how the concrete will be mixed and delivered, and how it will be placed to form this structure.

Cement

Portland cement is the most common type of cement in general usage. It is a basic ingredient of concrete, mortar, and plaster. English masonry worker Joseph Aspdin patented Portland cement in 1824; it was named because of its similarity in colour to Portland limestone, quarried from the English Isle of Portland and used extensively in London architecture. It consists of a mixture of oxides of calcium, silicon and aluminium. Portland cement and similar materials are made by heating limestone (a source of calcium) with clay, and grinding this product (called *clinker*) with a source of sulfate (most commonly gypsum).

Water

Combining water with a cementitious material forms a cement paste by the process of hydration. The cement paste glues the aggregate together, fills voids within it, and allows it to flow more freely.

Less water in the cement paste will yield a stronger, more durable concrete; more water will give an freer-flowing concrete with a higher slump. Impure water used to make concrete can cause problems when setting or in causing premature failure of the structure.

Hydration involves many different reactions, often occurring at the same time. As the reactions proceed, the products of the cement hydration process gradually bond together the individual sand and gravel particles, and other components of the concrete, to form a solid mass.

Reaction:

Cement chemist notation: $C_3S + H \rightarrow C\text{-}S\text{-}H + CH$
Standard notation: $Ca_3SiO_5 + H_2O \rightarrow (CaO)\cdot(SiO_2)\cdot(H_2O)(gel) + Ca(OH)_2$
Balanced: $2Ca_3SiO_5 + 7H_2O \rightarrow 3(CaO)\cdot2(SiO_2)\cdot4(H_2O)(gel) + 3Ca(OH)_2$

Aggregates

Cement and sand ready to be mixed.

Fine and coarse aggregates make up the bulk of a concrete mixture. Sand, natural gravel and crushed stone are mainly used for this purpose. Recycled aggregates (from construction, demolition and excavation waste) are increasingly used as partial replacements of natural aggregates, while a number of manufactured aggregates, including air-cooled blast furnace slag and bottom ash are also permitted.

Decorative stones such as quartzite, small river stones or crushed glass are sometimes added to the surface of concrete for a decorative "exposed aggregate" finish, popular among landscape designers.

The presence of aggregate greatly increases the robustness of concrete over and above that of cement, which otherwise is a brittle material, and thus concrete is a true composite material.

Redistribution of aggregates after compaction often creates inhomogeneity due to the influence of vibration. As a result, gradients of strength may be significant.

Reinforcement

Installing rebar in a floor slab during a concrete pour.

Concrete is strong in compression, as the aggregate efficiently carries the compression load. However, it is weak in tension as the cement holding the aggregate in place can crack, allowing the structure to fail. Reinforced concrete solves these problems by adding either steel reinforcing bars, steel fibers, glass fiber, or plastic fiber to carry tensile loads. Thereafter the concrete is reinforced to withstand the tensile loads upon it.

Chemical admixtures

Chemical admixtures are materials in the form of powder or fluids that are added to the concrete to give it certain characteristics not obtainable with plain concrete mixes. In normal use, admixture dosages are less than 5% by mass of cement, and are added to the concrete at the time of batching/mixing. The common types of admixtures are as follows.

- Accelerators speed up the hydration (hardening) of the concrete. Typical materials used are $CaCl_2$, $Ca(NO_3)_2$ and $NaNO_3$. However, use of chlorides may cause

corrosion in steel reinforcing and is prohibited in some countries and therefore nitrates may be favoured.

- Retarders slow the hydration of concrete, and are used in large or difficult pours where partial setting before the pour is complete is undesirable. Typical polyol retarders are sugar, sucrose, sodium gluconate, glucose, citric acid, and tartaric acid.
- Air entrainments add and entrain tiny air bubbles in the concrete, which will reduce damage during freeze-thaw cycles thereby increasing the concrete's durability. However, entrained air is a trade-off with strength, as each 1% of air may result in 5% decrease in compressive strength.
- Plasticizers increase the workability of plastic or "fresh" concrete, allowing it be placed more easily, with less consolidating effort. Typical plasticizers are lignosulfonate. Plasticizers can be used to reduce the water content of a concrete while maintaining workability, and are sometimes called *water-reducers* due to this use. Such treatment improves its strength and durability characteristics. Superplasticizers (also called *high-range water-reducers*) are a class of plasticizers that have fewer deleterious effects, and can be used to increase workability more than practical with traditional plasticizers. Compounds used as superplasticizers include sulfonated naphthalene formaldehyde condensate, sulfonated melamine formaldehyde condensate, acetone formaldehyde condensate, and polycarboxylate ethers.
- Pigments can be used to change the color of concrete, for aesthetics.
- Corrosion inhibitors are used to minimize the corrosion of steel and steel bars in concrete.
- Bonding agents are used to create a bond between old and new concrete.
- Pumping aids improve pumpability, thicken the paste, and reduce separation and bleeding.

Blocks of concrete in Belo Horizonte, Brazil.

Mineral admixtures and blended cements

There are inorganic materials that also have pozzolanic or latent hydraulic properties. These very fine-grained materials are added to the concrete mix to improve the properties of concrete (mineral admixtures), or as a replacement for Portland cement (blended cements).

- Fly ash: A by product of coal fired electric generating plants, it is used to partially replace Portland cement (by up to 60% by mass). The properties of fly ash depend on the type of coal burnt. In general, silicious fly ash is pozzolanic, while calcareous fly ash has latent hydraulic properties.

- Ground granulated blast furnace slag (GGBFS or GGBS): A by-product of steel production is used to partially replace Portland cement (by up to 80% by mass). It has latent hydraulic properties.
- Silica fume: A by-product of the production of silicon and ferrosilicon alloys. Silica fume is similar to fly ash, but has a particle size 100 times smaller. This results in a higher surface to volume ratio and a much faster pozzolanic reaction. Silica fume is used to increase strength and durability of concrete, but generally requires the use of superplasticizers for workability.
- High reactivity Metakaolin (HRM): Metakaolin produces concrete with strength and durability similar to concrete made with silica fume. While silica fume is usually dark gray or black in color, high reactivity metakaolin is usually bright white in color, making it the preferred choice for architectural concrete where appearance is important.

Concrete production

Concrete plant facility (background) with concrete delivery trucks.

The processes used vary dramatically, from hand tools to heavy industry, but result in the concrete being placed where it cures into a final form. Wide range of technological factors may occur during production of concrete elements and their influence to basic characteristics may vary

When initially mixed together, Portland cement and water rapidly form a gel, formed of tangled chains of interlocking crystals. These continue to react over time, with the initially fluid gel often aiding in placement by improving workability. As the concrete sets, the chains of crystals join up, and form a rigid structure, gluing the aggregate particles in place. During curing, more of the cement reacts with the residual water (hydration).

This curing process develops physical and chemical properties. Among other qualities, mechanical strength, low moisture permeability, and chemical and volumetric stability.

Cement being mixed with sand and water to form concrete.

Mixing concrete

Thorough mixing is essential for the production of uniform, high quality concrete. Therefore, equipment and methods should be capable of effectively mixing concrete materials containing the largest specified aggregate to produce *uniform mixtures* of the lowest slump practical for the work.

Separate paste mixing has shown that the mixing of cement and water into a paste before combining these materials with aggregates can increase the compressive strength of the resulting concrete. The paste is generally mixed in a *high-speed*, shear-type mixer at a w/cm (water to cement ratio) of 0.30 to 0.45 by mass. The cement paste premix may include admixtures such as accelerators or retarders, plasticizers, pigments, or silica fume. The premixed paste is then blended with aggregates and any remaining batch water, and final mixing is completed in conventional concrete mixing equipment.

High-energy mixed (HEM) concrete is produced by means of high-speed mixing of cement, water, and sand with net specific energy consumption of at least 5 kilojoules per kilogram of the mix. A plasticizer or a superplasticizer is then added to the activated mixture, which can later be mixed with aggregates in a conventional concrete mixer. In this process, sand provides dissipation of energy and creates high shear conditions on the surface of cement particles. This results in the full volume of water interacting with cement. The liquid activated mixture can be used by itself or foamed (expanded) for lightweight concrete. HEM concrete hardens in low and subzero temperature conditions and possesses an increased volume of gel, which drastically reduces capillarity in solid and porous materials.

Pouring a concrete floor for a commercial building, *slab-on-ground*.

Concrete pump

A concrete slab ponded while curing.

Workability

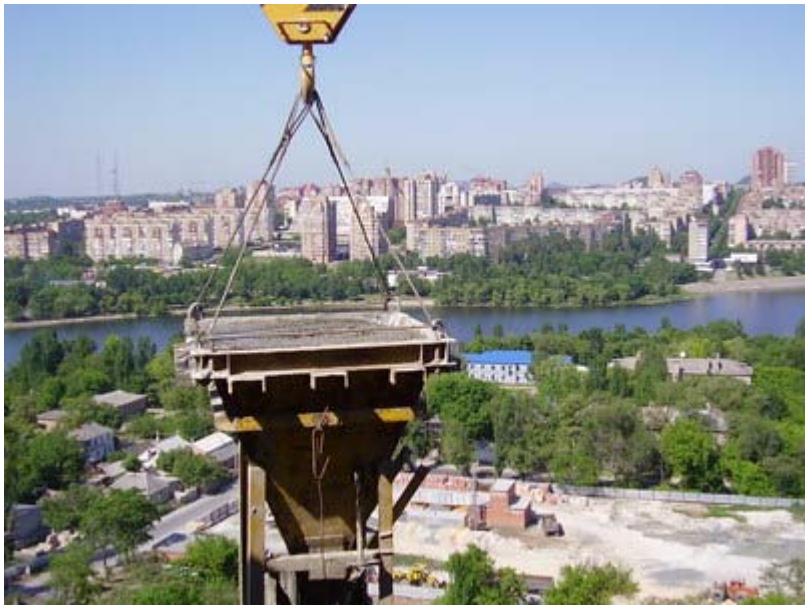
Workability is the ability of a fresh (plastic) concrete mix to fill the form/mold properly with the desired work (vibration) and without reducing the concrete's quality. Workability depends on water content, aggregate (shape and size distribution), cementitious content and age (level of hydration), and can be modified by adding chemical admixtures, like superplasticizer. Raising the water content or adding chemical admixtures will increase concrete workability. Excessive water will lead to increased bleeding (surface water) and/or segregation of aggregates (when the cement and aggregates start to separate), with the resulting concrete having reduced quality. The use of an aggregate with an undesirable gradation can result in a very harsh mix design with a very low slump, which cannot be readily made more workable by addition of reasonable amounts of water.

Workability can be measured by the concrete slump test, a simplistic measure of the plasticity of a fresh batch of concrete following the ASTM C 143 or EN 12350-2 test standards. Slump is normally measured by filling an "Abrams cone" with a sample from a fresh batch of concrete. The cone is placed with the wide end down onto a level, non-absorptive surface. It is then filled in three layers of equal volume, with each layer being tamped with a steel rod in order to consolidate the layer. When the cone is carefully lifted off, the enclosed material will slump a certain amount due to gravity. A relatively dry sample will slump very little, having a slump value of one or two inches (25 or 50 mm). A relatively wet concrete sample may slump as much as eight inches. Workability can also be measured by using the Flow table test.

Slump can be increased by adding chemical admixtures such as plasticizer or superplasticizer without changing the water-cement ratio. Some other admixtures, especially air-entraining admixture, can increase the slump of a mix.

High-flow concrete, like self-consolidating concrete, is tested by other flow-measuring methods. One of these methods includes placing the cone on the narrow end and observing how the mix flows through the cone while it is gradually lifted.

After mixing, concrete is a fluid and can be pumped to where it is needed.



Concrete mixture placement

Concrete compaction

Curing

In all but the least critical applications, care needs to be taken to properly *cure* concrete, and achieve best strength and hardness. This happens after the concrete has been placed. Cement requires a moist, controlled environment to gain strength and harden fully. The cement paste hardens over time, initially setting and becoming rigid though very weak, and gaining in strength in the weeks following. In around 3 weeks, over 90% of the final strength is typically reached, though it may continue to strengthen for decades.

Hydration and hardening of concrete during the first three days is critical. Abnormally fast drying and shrinkage due to factors such as evaporation from wind during placement may lead to increased tensile stresses at a time when it has not yet gained significant strength, resulting in greater shrinkage cracking. The early strength of the concrete can be increased by keeping it damp for a longer period during the curing process. Minimizing stress prior to curing minimizes cracking. High early-strength concrete is designed to hydrate faster, often by increased use of cement that increases shrinkage and cracking. Strength of concrete changes (increases) up to three years. It depends on cross-section dimension of elements and conditions of structure exploitation.

During this period concrete needs to be in conditions with a controlled temperature and humid atmosphere. In practice, this is achieved by spraying or ponding the concrete surface with water, thereby protecting concrete mass from ill effects of ambient conditions. The pictures to the right show two of many ways to achieve this, ponding – submerging setting concrete in water, and wrapping in plastic to contain the water in the mix.

Properly curing concrete leads to increased strength and lower permeability, and avoids cracking where the surface dries out prematurely. Care must also be taken to avoid freezing, or overheating due to the exothermic setting of cement (the Hoover Dam used pipes carrying coolant during setting to avoid damaging overheating). Improper curing can cause scaling, reduced strength, poor abrasion resistance, and cracking.

Properties

Concrete has relatively high compressive strength, but significantly lower tensile strength, and as such is usually reinforced with materials that are strong in tension (often steel). The elasticity of concrete is relatively constant at low stress levels but starts decreasing at higher stress levels as matrix cracking develops. Concrete has a very low coefficient of thermal expansion, and as it matures concrete shrinks. All concrete structures will crack to some extent, due to shrinkage and tension. Concrete that is subjected to long-duration forces is prone to creep.

Tests can be made to ensure the properties of concrete correspond to specifications for the application.

Environmental concerns

Carbon dioxide emissions and climate change

The cement industry is one of two primary producers of carbon dioxide (CO_2), creating up to 5% of worldwide man-made emissions of this gas, of which 50% is from the chemical process, and 40% from burning fuel. The embodied carbon dioxide (ECO_2) of one tonne of concrete is around 100 kg/tonne. The CO_2 emission from the concrete production is directly proportional to the cement content used in the concrete mix. Indeed, 900 kg of CO_2 are emitted for the fabrication of every ton of cement. Cement

manufacture contributes greenhouse gases both directly through the production of carbon dioxide when calcium carbonate is thermally decomposed, producing lime and carbon dioxide, and also through the use of energy, particularly from the combustion of fossil fuels. However, some companies have recognized the problem and are envisaging solutions to counter their CO_2 emissions. The principle of carbon capture and storage consists of directly capturing the CO_2 at the outlet of the cement kiln in order to transport it and to store the captured CO_2 in an adequate and deep geological formation.

Surface runoff

Surface runoff, when water runs off impervious surfaces, such as non-porous concrete, can cause heavy soil erosion. Urban runoff tends to pick up gasoline, motor oil, heavy metals, trash and other pollutants from sidewalks, roadways and parking lots. The impervious cover in a typical urban area limits groundwater percolation and causes five times the amount of runoff generated by a typical woodland of the same size. A 2008 report by the United States National Research Council identified urban runoff as a leading source of water quality problems.

Urban heat

Both concrete and asphalt are the primary contributors to what is known as the urban heat island effect.

Using light-colored concrete has proven effective in reflecting up to 50% more light than asphalt and reducing ambient temperature. A low albedo value, characteristic of black asphalt, absorbs a large percentage of solar heat and contributes to the warming of cities. By paving with light colored concrete, in addition to replacing asphalt with light-colored concrete, communities can lower their average temperature.

In many U.S. cities, pavement covers about 30-40% of the surface area. This directly affects the temperature of the city, and contributes to the urban heat island effect. Paving with light-colored concrete would lower temperatures of paved areas and improve nighttime visibility. The potential of energy saving within an area is also high. With lower temperatures, the demand for air conditioning decreases, saving energy.

Atlanta has tried to mitigate the heat-island effect. City officials noted that when using heat-reflecting concrete, their average city temperature decreased by 6 °F. The Design Trust for Public Space found that by slightly raising the albedo value in in New York City, beneficial effects such as energy savings could be achieved. It was concluded that this could be accomplished by the replacement of black asphalt with light-colored concrete.

However, in winter this may be a disadvantage as ice will form more easily and remain longer on the light colored surfaces as they will be colder due to less energy absorbed from the reduced amount of sunlight in winter.

Concrete dust

Building demolition and natural disasters such as earthquakes often release a large amount of concrete dust into the local atmosphere. Concrete dust was concluded to be the major source of dangerous air pollution following the Great Hanshin earthquake.

Health concerns

The presence of some substances in concrete, including useful and unwanted additives, can cause health concerns. Natural radioactive elements (K, U and Th) can be present in various concentration in concrete dwellings, depending on the source of the raw materials used. Toxic substances may also be added to the mixture for making concrete by unscrupulous makers. Dust from rubble or broken concrete upon demolition or crumbling may cause serious health concerns depending also on what had been incorporated in the concrete.

Concrete handling/safety precautions

Handling of wet concrete must always be done with proper protective equipment. Contact with wet concrete can cause skin chemical burns due to the caustic nature of the mixture of cement and water. Indeed, the pH of fresh cement water is highly alkaline due to the presence of free potassium and sodium hydroxides in solution (pH ~ 13.5). Eyes, hands and feet must be correctly protected to avoid any direct contact with wet concrete and washed without delay if necessary.

Secondary efflorescence. Water seeping through the concrete, often in cracks, having dissolved components of concrete.

Damage modes

Concrete spalling caused by the corrosion of reinforcement bars after that carbonation of cement decreased the pH below the passivation threshold for steel.

Concrete can be damaged by many processes, such as the expansion of corrosion products of the steel reinforcement bars, freezing of trapped water, fire or radiant heat, aggregate expansion, sea water effects, bacterial corrosion, leaching, erosion by fast-flowing water, physical damage and chemical damage (from carbonation, chlorides, sulfates and distillate water).

Concrete repair

Concrete pavement preservation (CPP) and concrete pavement restoration (CPR) are techniques used to manage the rate of pavement deterioration on concrete streets, highways and airports. Without changing concrete grade, this non-overlay method is used to repair isolated areas of distress. CPP and CPR techniques include slab stabilization, full- and partial-depth repair, dowel bar retrofit, cross stitching longitudinal cracks or joints, diamond grinding and joint and crack resealing. CPR methods, developed over the last 40 years, are utilized in lieu of short-lived asphalt overlays and bituminous patches to

repair roads. These methods are often less expensivethan an asphalt overlay but last three times longer and provide a greener solution.

CPR techniques can be used to address specific problems or bring a pavement back to its original quality. When repairing a road, design data, construction data, traffic data, environmental data, previous CPR activities and pavement condition, must all be taken into account. Pavements repaired using CPR methods usually last 15 years. The methods are described below.

- Slab stabilization restores support to concrete slabs by filling small voids that develop underneath the concrete slab at joints, cracks or the pavement edge.
- Full-depth repairs fixes cracked slabs and joint deterioration by removing at least a portion of the existing slab and replacing it with new concrete.
- Partial-depth repairs corrects surface distress and joint-crack deterioration in the upper third of the concrete slab. Placing a partial-depth repair involves removing the deteriorated concrete, cleaning the patch area and placing new concrete.
- Dowel bar retrofit consists of cutting slots in the pavement across the joint or crack, cleaning the slots, placing the dowel bars and backfilling the slots with new concrete. Dowel bar retrofits link slabs together at transverse cracks and joints so that the load is evenly distributed across the crack or joint.
- Cross-stitching longitudinal cracks or joints repairs low-severity longitudinal cracks. This method adds reinforcing steel to hold the crack together tightly.
- Diamond grinding, by removing faulting, slab warping, studded tire wear and unevenness resulting from patches, diamond grinding creates a smooth, uniform pavement profile. Diamond grinding reduces road noise by providing a longitudinal texture, which is quieter than transverse textures. The longitudinal texture also enhances surface texture and skid resistance in polished pavements.
- Joint and crack sealing minimizes the infiltration of surface water and incompressible material into the joint system. Minimizing water entering the joint reduces sub-grade softening, slows pumping and erosion of the sub-base fines, and may limit dowel-bar corrosion caused by de-icing chemicals.

Concrete recycling

Concrete recycling is an increasingly common method of disposing of concrete structures. Concrete debris was once routinely shipped to landfills for disposal, but recycling is increasing due to improved environmental awareness, governmental laws, and economic benefits.

Concrete, which must be free of trash, wood, paper and other such materials, is collected from demolition sites and put through a crushing machine, often along with asphalt, bricks, and rocks.

Reinforced concrete contains rebar and other metallic reinforcements, which are removed with magnets and recycled elsewhere. The remaining aggregate chunks are sorted by size. Larger chunks may go through the crusher again. Smaller pieces of concrete are used as

gravel for new construction projects. Aggregate base gravel is laid down as the lowest layer in a road, with fresh concrete or asphalt placed over it. Crushed recycled concrete can sometimes be used as the dry aggregate for brand new concrete if it is free of contaminants, though the use of recycled concrete limits strength and is not allowed in many jurisdictions. On March 3, 1983, a government funded research team (the VIRL research.codep) approximated that almost 17% of worldwide landfill was by-products of concrete based waste.

Recycling concrete provides environmental benefits, conserving landfill space and use as aggregate reduces the need for gravel mining.

World records

The world record for the largest concrete pour in a single project is the Three Gorges Dam in Hubei Province, China by the Three Gorges Corporation. The amount of concrete used in the construction of the dam is estimated at 16 million cubic meters over 17 years. The previous record was 3.2 million cubic meters held by Itaipu hydropower station in Brazil.

Concrete pumping

The world record was set at on 7 August 2009 during the construction of the Parbati Hydroelectric Project, near the village of Suind, Himachal Pradesh, India, when the concrete mix was pumped through a vertical height of 715 m (2,346 ft).

Continuous pours

The world record for largest continuously poured concrete raft was achieved in August 2007 in Abu Dhabi by contracting firm, Al Habtoor-CCC Joint Venture. The pour (a part of the foundation for the Abu Dhabi's Landmark Tower) was 16,000 cubic meters of concrete poured within a two day period. The previous record (close to 10,500 cubic meters) was held by Dubai Contracting Company and achieved March 23, 2007.

The world record for largest continuously poured concrete floor was completed November 8, 1997, in Louisville, Kentucky by design-build firm, EXXCEL Project Management. The monolithic placement consisted of 225,000 square feet (20,900 m^2) of concrete placed within a 30 hour period, finished to a flatness tolerance of F_F 54.60 and a levelness tolerance of F_L 43.83. This surpassed the previous record by 50% in total volume and 7.5% in total area.

The record for the largest continuously placed underwater concrete pour was completed October 18, 2010, in New Orleans, Louisiana by contractor, C.J. Mahan Construction Company, LLC, out of Grove City, Ohio. The placement consisted of 10,224 cubic yards of concrete placed in a 58 hour period using two concrete pumps and two dedicated concrete batch plants. Upon curing, this placement will allow the 50,180 square foot

cofferdam to be dewatered approximately 26 feet below sea level to allow the construction of the IHNC GIWW Sill & Monolith Project to be completed in the dry.

The interior of the Pantheon in the 18th century, painted by Giovanni Paolo Pannini.

Use of concrete in infrastructure

Mass concrete structures

These include gravity dams such as the Hoover Dam, the Itaipu Dam, and the Three Gorges Dam and large breakwaters. Concrete that is poured all at once in one block (so that there are no weak points where the concrete is "welded" together) is used for tornado shelters.

Reinforced concrete structures

Reinforced concrete contains steel reinforcing that is designed and placed in the structure at specific positions to cater for all the stress conditions that the structure is required to accommodate.

Prestressed concrete structures

Prestressed concrete is a form of reinforced concrete that builds in compressive stresses during construction to oppose those found when in use. This can greatly reduce the weight of beams or slabs, by better distributing the stresses in the structure to make optimal use of the reinforcement. For example a horizontal beam will tend to sag down. If the reinforcement along the bottom of the beam is prestressed, it can counteract this.

In pre-tensioned concrete, the prestressing is achieved by using steel or polymer tendons or bars that are subjected to a tensile force prior to casting, or for post-tensioned concrete, after casting.

Concrete textures

When one thinks of concrete, the image of a dull, gray concrete wall often comes to mind. With the use of form liner, concrete can be cast and molded into different textures and used for decorative concrete applications. Sound/retaining walls, bridges, office buildings and more serve as the optimal canvases for concrete art. For example, the Pima Freeway/Loop 101 retaining and sound walls in Scottsdale, Arizona, feature desert flora and fauna, a 67-foot (20 m) lizard and 40-foot (12 m) cacti along the 8-mile (13 km) stretch. The project, titled "The Path Most Traveled," is one example of how concrete can be shaped using elastomeric form liner.

40-foot cacti decorate a sound/retaining wall in Scottsdale, AZ.

Building with concrete

Concrete is one of the most durable building materials. It provides superior fire resistance compared with wooden construction, can gain strength over time. Structures made of concrete can have a long service life. Concrete is the most widely used construction material in the world with annual consumption estimated at between 21 and 31 billion tonnes.

Environmentally sustainable

With its 100-year service life, concrete conserves resources by reducing the need for reconstruction. Its ingredients are cement and readily available natural materials: water, aggregate (sand and gravel or crushed stone). Concrete does not require any CO_2 absorbing trees to be cut down. The land required to extract the materials needed to make concrete is only a fraction of that used to harvest forests for lumber.

The Baths of Caracalla, Rome, Italy, in 2003.

Concrete absorbs CO_2 throughout its lifetime through carbonation, helping reduce its carbon footprint. A recent study indicates that in countries with the most favorable recycling practices, it is realistic to assume that approximately 86% of the concrete is carbonated after 100 years. During this time, the concrete will absorb approximately 57% of the CO_2 emitted during the original calcination. About 50% of the CO_2 is absorbed within a short time after concrete is crushed during recycling operations.

Concrete consists of between 7% and 15% cement, its only energy-intensive ingredient. A study comparing the CO_2 emissions of several different building materials for construction of residential and commercial buildings found that concrete accounted for 147 kg of CO_2 per 1000 kg used, metals accounted for 3000 kg of CO_2 and wood accounted for 127 kg of CO_2. The quantity of CO_2 generated during the cement manufacturing process can be reduced by changing the raw materials used in its manufacture.

A new environmentally friendly blend of cement known as Portland-limestone cement (PLC) is gaining ground all over the world. It contains up to 15% limestone, rather than the 5% in regular Portland cement and results in 10% less CO_2 emissions from production with no impact on product performance. Concrete made with PLC performs similarly to concrete made with regular cement and thus PLC-based concrete can be widely used as a replacement. In Europe, PLC-based concrete has replaced about 40% of

general use concrete. In Canada, PLC will be included in the National Building Code in 2010. The approval of PLC is still under consideration in the United States.

Energy efficiency

Energy requirements for transportation of concrete are low because it is produced locally from local resources, typically manufactured within 100 kilometers of the job site. Once in place, concrete offers significant energy efficiency over the lifetime of a building. Concrete walls leak air far less than those made of wood-frames. Air leakage accounts for a large percentage of energy loss from a home. The thermal mass properties of concrete increase the efficiency of both residential and commercial buildings. By storing and releasing the energy needed for heating or cooling, concrete's thermal mass delivers year-round benefits by reducing temperature swings inside and minimizing heating and cooling costs. While insulation reduces energy loss through the building envelope, thermal mass uses walls to store and release energy. Modern concrete wall systems use both insulation and thermal mass to create an energy-efficient building. Insulating Concrete Forms (ICFs) are hollow blocks or panels made of either insulating foam or rastra that are stacked to form the shape of the walls of a building and then filled with reinforced concrete to create the structure.

Models of Porsche automobiles, made out of concrete, part of an exhibition, "Best of Austria," in the Lentos Museum in Linz, Austria in 2009.

Fire safety and quality of life

Concrete buildings are more resistant to fire than those constructed using wood or steel frames. Since concrete does not burn and stops fire from spreading, it offers total fire protection for occupants and their property. Concrete reduces the risk of structural collapse and is an effective fire shield, providing safe means of escape for occupants and protection for firefighters. Furthermore, it does not produce any smoke or toxic gases and does not drip molten particles, which can spread fire. Neither heat, flames nor the water used to extinguish a fire seriously affect the structure of concrete walls and floors making repairs after a fire a relatively simple task.

A study was conducted in Sweden by Olle Lundberg on the cost of fire damage associated with larger fires in multi-unit buildings, based on statistics from the insurance association in Sweden (Försäkringsförbundet). The study was limited to buildings with an insured value greater than €150,000. It covered 125 fires that occurred between 1995 and 2004, about 10% of the fires in multi-family homes, but 56% of the major fires. The results showed that:

- the average insurance payout per fire, per unit in wood frame buildings was around five times that of fires in concrete buildings (approximately €50,000 compared with €10,000)
- a major fire is more than 11 times more likely to develop in a wood-frame house than in one built using concrete
- among the burned houses, 50% of those made with wood had to be demolished, whereas only 9% of the concrete ones were beyond repair
- the fire spread to neighbouring apartments in only three of the 55 fires in concrete houses
- of those 55 fires, 45 were in attics and roofing

Options for non-combustible construction include floors, ceilings and roofs made of cast-in-place and hollow-core precast concrete. For walls, concrete masonry technology and Insulating Concrete Forms (ICFs) are additional options. ICFs are hollow blocks or panels made of fire-proof insulating foam that are stacked to form the shape of the walls of a building and then filled with reinforced concrete to create the structure.

“Fire-wall” tests, in which ICF walls were subjected to a continuous gas flame with a temperature of more than 1000°C for as long as 4 hours showed no significant breaks in the concrete layer or dangerous transmission of heat. In comparison, wood frame walls normally collapse in an hour or less under these conditions. Concrete provides stable compartmentation in large industrial and multi-storey buildings so a fire starting in one section does not spread to others.

Using concrete to construct buildings offers the best possible protection and safety in fires:

- it does not burn or add to fire load

- it has high resistance to fire, preventing it from spreading thus reduces resulting environmental pollution
- it does not produce any smoke, toxic gases or drip molten particles
- it reduces the risk of structural collapse
- it provides safe means of escape for occupants and access for firefighters as it is an effective fire shield
- it is not affected by the water used to put out a fire
- it is easy to repair after a fire and thus helps residents and businesses recover sooner
- it resists extreme fire conditions, making it ideal for storage facilities with a high fire load
- it provides complete fire protection so there is normally no need for additional measures

Recycled crushed concrete being loaded into a semi-dump truck to be used as granular fill.

Concrete also provides the best resistance of any building material to high winds, hurricanes, tornadoes due to its lateral stiffness that results in minimal horizontal movement. When properly designed for ductility, it also provides superior resistance to seismic events. It does not rust, rot or sustain growth of mold and stands up well to the freeze – thaw cycle. As a result of all these benefits, insurance for concrete homes is often 15 to 25 percent lower than for comparable wood frame homes.

Concrete buildings also have excellent indoor air quality with no off-gassing, toxicity and release of volatile organic compounds so they are generally healthier to live in than those made of wood or steel. As it is practically inert and waterproof, concrete does not need volatile organic-based preservatives, special coatings or sealers. Concrete can be easily cleaned with organic, non-toxic substances. Its sound insulating properties make buildings and homes a quiet and comfortable living environment. After accounting for sound passing through windows, a concrete home is about two-thirds quieter than a comparable wood-frame home.

Due to the long life of concrete structures, their impacts on the environment are negligible. Once built, they have minimal maintenance requirements and as a result minimal social disruption. Using concrete reduces construction waste as it is used on an as-required basis, thereby minimizing the waste put into landfills.

Recycling and recyclable

A nearly inert material, concrete is suitable as a medium for recycling waste and industrial byproducts. Fly ash, slag and silica fume are used in making concrete, which helps reduce embodied energy, carbon footprint and quantity of landfill materials. The process of making cement also uses waste materials. Tires have high energy content and can supplement coal as fuel in the kiln. Industrial byproducts such as ash from coal combustion, fly ash from power stations as well as mill scale and foundry sand from steel casting provide the silica, calcium, alumina and iron needed for making cement. Even kiln dust, a solid waste generated by cement manufacturing, is often recycled back into the kiln as a raw material. Old concrete that has reached the end of its service life can be recycled and reused as granular fill for road beds.

Chapter 11

Earthing System

In electricity supply systems, an **earthing system** defines the electrical potential of the conductors relative to that of the Earth's conductive surface. The choice of earthing system has implications for the safety and electromagnetic compatibility of the power supply. Note that regulations for earthing (grounding) systems vary considerably among different countries.

A *protective earth* (PE) connection ensures that all exposed conductive surfaces are at the same electrical potential as the surface of the Earth, to avoid the risk of electrical shock if a person touches a device in which an insulation fault has occurred. It ensures that in the case of an insulation fault (a "short circuit"), a very high current flows, which will trigger an overcurrent protection device (fuse, circuit breaker) that disconnects the power supply.

A *functional earth* connection serves a purpose other than providing protection against electrical shock. In contrast to a protective earth connection, a functional earth connection may carry a current during the normal operation of a device. Functional earth connections may be required by devices such as surge suppression and electromagnetic interference filters, some types of antennas and various measurement instruments. Generally the protective earth is also used as a functional earth, though this requires care in some situations.

IEC terminology

International standard IEC 60364 distinguishes three families of earthing arrangements, using the two-letter codes **TN**, **TT**, and **IT**.

The first letter indicates the connection between earth and the power-supply equipment (generator or transformer):

T

Direct connection of a point with earth (Latin: terra);

I
: No point is connected with earth (isolation), except perhaps via a high impedance.

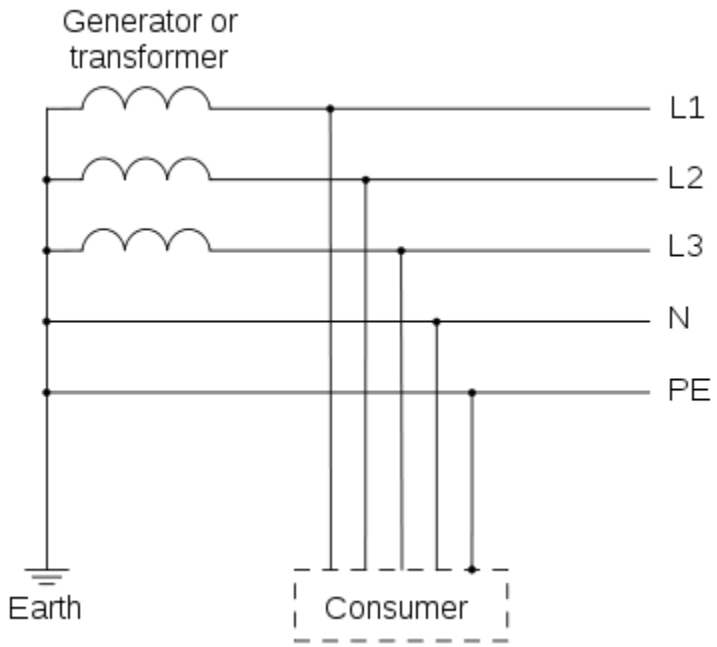
The second letter indicates the connection between earth and the electrical device being supplied:

T
: Direct connection of a point with earth

N
: Direct connection to neutral at the origin of installation, which is connected to the earth

TN networks

In a **TN** earthing system, one of the points in the generator or transformer is connected with earth, usually the star point in a three-phase system. The body of the electrical device is connected with earth via this earth connection at the transformer.



The conductor that connects the exposed metallic parts of the consumer is called *protective earth* (*PE*). The conductor that connects to the star point in a three-phase system, or that carries the return current in a single-phase system, is called *neutral* (*N*). Three variants of TN systems are distinguished:

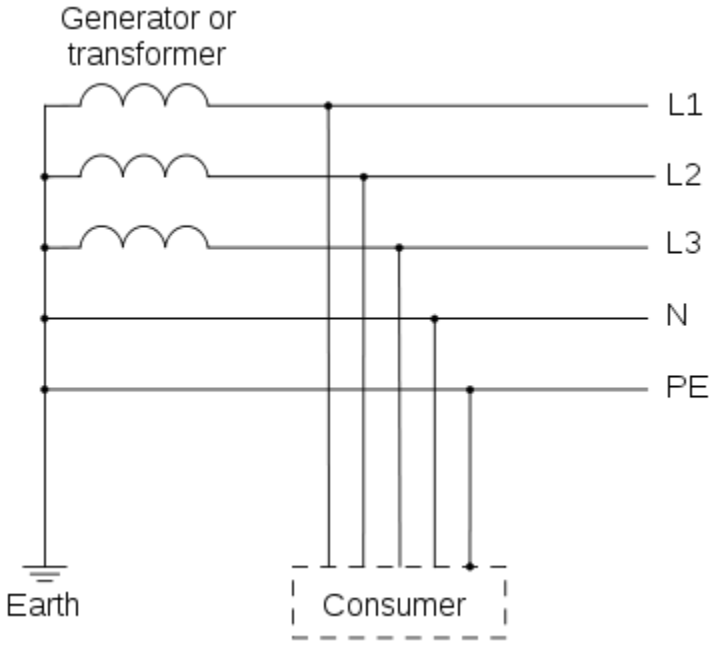
TN−S
: PE and N are separate conductors that are connected together only near the power source.

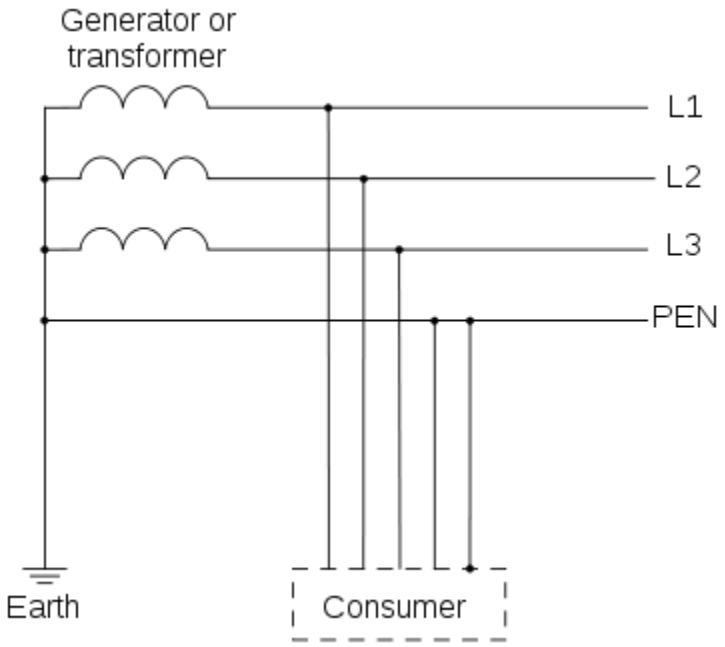
TN−C

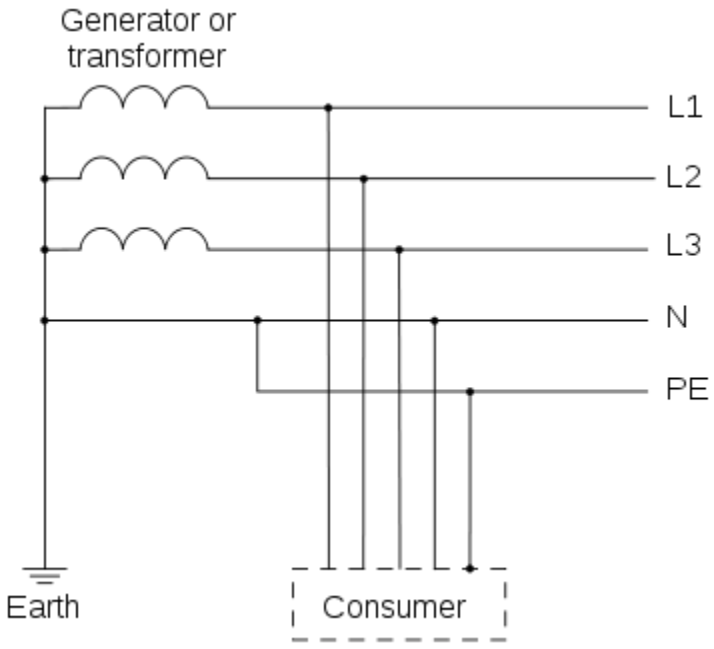
A combined PEN conductor fulfills the functions of both a PE and an N conductor. Rarely used.

TN−C−S

Part of the system uses a combined PEN conductor, which is at some point split up into separate PE and N lines. The combined PEN conductor typically occurs between the substation and the entry point into the building, and separated in the service head. In the UK, this system is also known as *protective multiple earthing (PME)*, because of the practice of connecting the combined neutral-and-earth conductor to real earth at many locations, to reduce the risk of broken neutrals - with a similar system in Australia being designated as *multiple earthed neutral (MEN)*.







TN-S: separate protective earth (PE) and neutral (N) conductors from transformer to consuming device, which are not connected together at any point after the building distribution point.
TN-C: combined PE and N conductor all the way from the transformer to the consuming device.

TN-C-S earthing system: combined PEN conductor from transformer to building distribution point, but separate PE and N conductors in fixed indoor wiring and flexible power cords.

It is possible to have both TN-S and TN-C-S supplies from the same transformer. For example, the sheaths on some underground cables corrode and stop providing good earth connections, and so homes where "bad earths" are found get converted to TN-C-S.

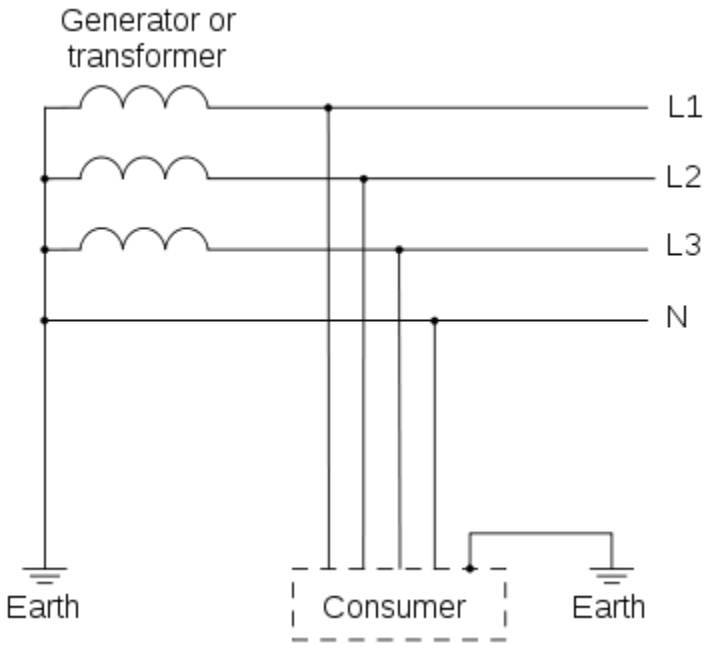
TT network

In a **TT** earthing system, the protective earth connection of the consumer is provided by a local connection to earth, independent of any earth connection at the generator.

The big advantage of the TT earthing system is the fact that it is clear of high and low frequency noises that come through the neutral wire from various electrical equipment connected to it. This is why TT has always been preferable for special applications like telecommunication sites that benefit from the interference-free earthing. Also, TT does not have the risk of a broken neutral.

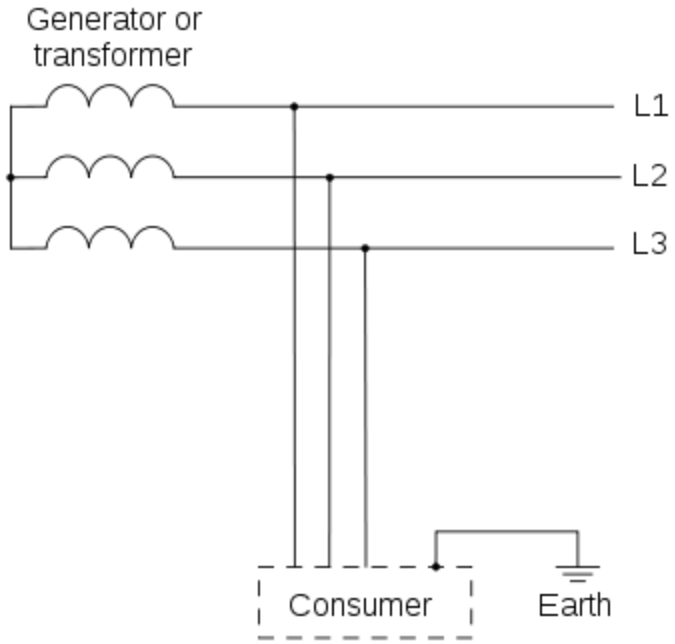
In locations where power is distributed overhead and TT is used, installation earth conductors are not at risk should any overhead distribution conductor be fractured by, say, a fallen tree or branch.

In pre-RCD era, the TT earthing system was unattractive for general use because of its worse capability of accepting high currents in case of a live-to-PE short circuit (in comparison with TN systems). But as residual current devices mitigate this disadvantage, the TT earthing system becomes attractive for premises where all AC power circuits are RCD-protected.



IT network

In an **IT** network, the distribution system has no connection to earth at all, or it has only a high impedance connection. In such systems, an insulation monitoring device is used to monitor the impedance. For safety reasons this network is not accepted under European norms.



Other terminologies

While the national wiring regulations for buildings of many countries follow the IEC 60364 terminology, in North America (United States and Canada), the term "equipment grounding conductor" refers to equipment grounds and ground wires on branch circuits, and "grounding electrode conductor" is used for conductors bonding an earth ground rod (or similar) to a service panel. "Grounded conductor" is the system "neutral".

Properties

Cost

- TN networks save the cost of a low-impedance earth connection at the site of each consumer. Such a connection (a buried metal structure) is required to provide *protective earth* in IT and TT systems.
- TN-C networks save the cost of an additional conductor needed for separate N and PE connections. However, to mitigate the risk of broken neutrals, special cable types and lots of connections to earth are needed.
- TT networks require proper RCD protection.

Fault path impedance

If the fault path between accidentally energized objects and the supply connection has low impedance, the fault current will be so large that the circuit overcurrent protection device (fuse or circuit breaker) will open to clear the ground fault. Where the earthing system does not provide a low-impedance metallic conductor between equipment enclosures and supply return (such as in a TT separately earthed system), fault currents are smaller, and will not necessarily operate the overcurrent protection device. In such case a residual current detector is installed to detect the current leaking to ground and interrupt the circuit.

Safety

- In TN, an insulation fault is very likely to lead to a high short-circuit current that will trigger an overcurrent circuit-breaker or fuse and disconnect the L conductors. With TT systems, the earth fault loop impedance can be too high to do this, or too high to do it quickly, so an RCD (or formerly ELCB) is usually employed. The provision of a Residual-current device (RCD) or ELCB to ensure safe disconnection makes these installations EEBAD (Earthed Equipotential Bonding and Automatic Disconnection).
- Many 1950s and earlier earlier TT installations in the UK may lack this important safety feature. Non-EEBAD installations are capable of the whole installation CPC (Circuit Protective Conductor) remaining live for extended periods under fault conditions, which is a real danger.
- In TN-S and TT systems (and in TN-C-S beyond the point of the split), a residual-current device can be used as an additional protection. In the absence of any

insulation fault in the consumer device, the equation $I_{L1}+I_{L2}+I_{L3}+I_N = 0$ holds, and an RCD can disconnect the supply as soon as this sum reaches a threshold (typically 10-500 mA). An insulation fault between either L or N and PE will trigger an RCD with high probability.

- In IT and TN-C networks, residual current devices are far less likely to detect an insulation fault. In a TN-C system, they would also be very vulnerable to unwanted triggering from contact between earth conductors of circuits on different RCDs or with real ground, thus making their use impracticable. Also, RCDs usually isolate the neutral core. Since it is unsafe to do this in a TN-C system, RCDs on TN-C should be wired to only interrupt the live conductor.
- In single-ended single-phase systems where the Earth and neutral are combined (TN-C, and the part of TN-C-S systems which uses a combined neutral and earth core), if there is a contact problem in the PEN conductor, then all parts of the earthing system beyond the break will rise to the potential of the L conductor. In an unbalanced multi-phase system, the potential of the earthing system will move towards that of the most loaded live conductor. Therefore, TN-C connections must not go across plug/socket connections or flexible cables, where there is a higher probability of contact problems than with fixed wiring. There is also a risk if a cable is damaged, which can be mitigated by the use of concentric cable construction and/or multiple earth electrodes. Due to the (small) risks of the lost neutral, use of TN-C-S supplies is banned for caravans and boats in the UK, and it is often recommended to make outdoor wiring TT with a separate earth electrode.
- In IT systems, a single insulation fault is unlikely to cause dangerous currents to flow through a human body in contact with earth, because no low-impedance circuit exists for such a current to flow. However, a first insulation fault can effectively turn an IT system into a TN system, and then a second insulation fault can lead to dangerous body currents. Worse, in a multi-phase system, if one of the live conductors made contact with earth, it would cause the other phase cores to rise to the phase-phase voltage relative to earth rather than the phase-neutral voltage. IT systems also experience larger transient overvoltages than other systems.
- In TN-C and TN-C-S systems, any connection between the combined neutral-and-earth core and the body of the earth could end up carrying significant current under normal conditions, and could carry even more under a broken neutral situation. Therefore, main equipotential bonding conductors must be sized with this in mind; use of TN-C-S is inadvisable in situations such as petrol stations, where there is a combination of lots of buried metalwork and explosive gases.

Electromagnetic compatibility

- In TN-S and TT systems, the consumer has a low-noise connection to earth, which does not suffer from the voltage that appears on the N conductor as a result of the return currents and the impedance of that conductor. This is of particular importance with some types of telecommunication and measurement equipment.
- In TT systems, each consumer has its own connection to earth, and will not notice any currents that may be caused by other consumers on a shared PE line.

Regulations

- In the United States National Electrical Code and Canadian Electrical Code the feed from the distribution transformer uses a combined neutral and grounding conductor, but within the structure separate neutral and protective earth conductors are used (TN-C-S). The neutral must be connected to the earth (ground) conductor only on the supply side of the customer's disconnecting switch. Additional connections of neutral to ground within the customer's wiring are prohibited.
- In Argentina, France (TT) and Australia (TN-C-S), the customers must provide their own ground connections.
- Japan is governed by PSE law, and uses TT earthing in most installations.
- In Australia, the Multiple Earthed Neutral (MEN) earthing system is used and is described in Section 5 of AS 3000. For an LV customer, it is a TN-C system from the transformer in the street to the premises, (the neutral is earhed multiple times along this segment), and a TN-S system inside the installation, from the Main Switchboard downwards. Looked at as a whole, it is a TN-C-S system.

Application examples

- Most modern homes in Europe have a TN-C-S earthing system. The combined neutral and earth occurs between the nearest transformer substation and the service cut out (the fuse before the meter). After this, separate earth and neutral cores are used in all the internal wiring.
- Older urban and suburban homes in the UK tend to have TN-S supplies, with the earth connection delivered through the lead sheath of the underground lead-and-paper cable.
- Some older homes, especially those built before the invention of residual-current circuit breakers and wired home area networks, use an in-house TN-C arrangement. This is no longer recommended practice.
- Laboratory rooms, medical facilities, construction sites, repair workshops, mobile electrical installations, and other environments that are supplied via engine-generators where there is an increased risk of insulation faults, often use an IT earthing arrangement supplied from isolation transformers. To mitigate the two-fault issues with IT systems, the isolation transformers should supply only a small number of loads each and/or should be protected with an insulation monitoring device (generally used only by medical, railway or military IT systems, because of cost).
- In remote areas, where the cost of an additional PE conductor outweighs the cost of a local earth connection, TT networks are commonly used in some countries, especially in older properties or in rural areas, where safety might otherwise be threatened by the fracture of an overhead PE conductor by, say, a fallen tree branch. TT supplies to individual properties are also seen in mostly TN-C-S systems where an individual property is considered unsuitable for TN-C-S supply.
- In Australia, and Israel the TN-C-S system is in use; however, the wiring rules currently state that, in addition, each customer must provide a separate connection

to earth via both a water pipe bond (if metallic water pipes enter the consumer's premises) and a dedicated earth electrode. In Australia, new installations must also bond the foundation concrete re-enforcing under wet areas to the earth conductor (AS3000), typically increasing the size of the earthing, and provides an equipotential plane in areas such as bathrooms. In older installations, it is not uncommon to find only the water pipe bond, and it is allowed to remain as such, but the additional earth electrode must be installed if any upgrade work is done. The protective earth and neutral conductors are combined until the consumer's neutral link (located on the customer's side of the electricity meter's neutral connection) - beyond this point, the protective earth and neutral conductors are separate.