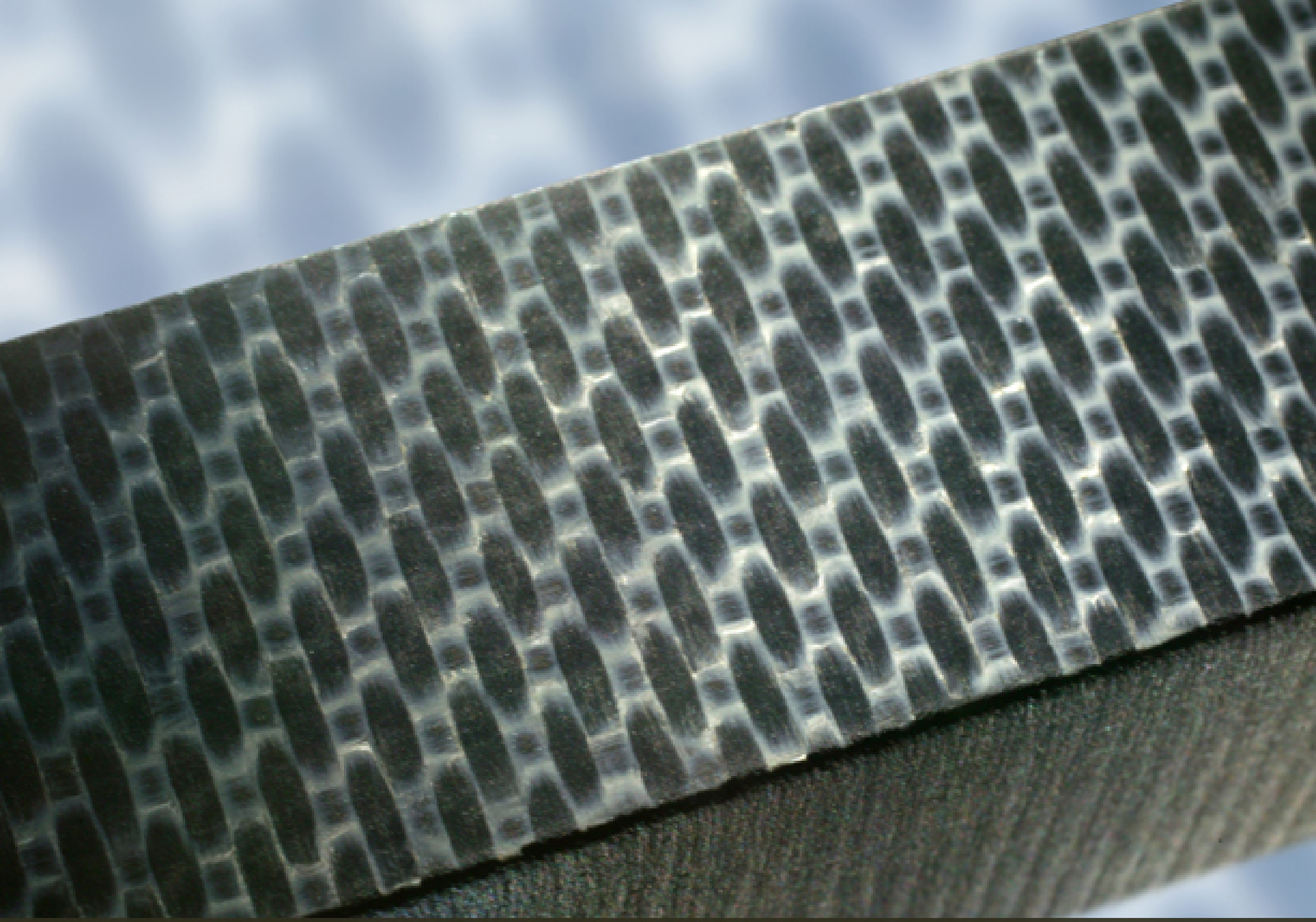

Composite Materials

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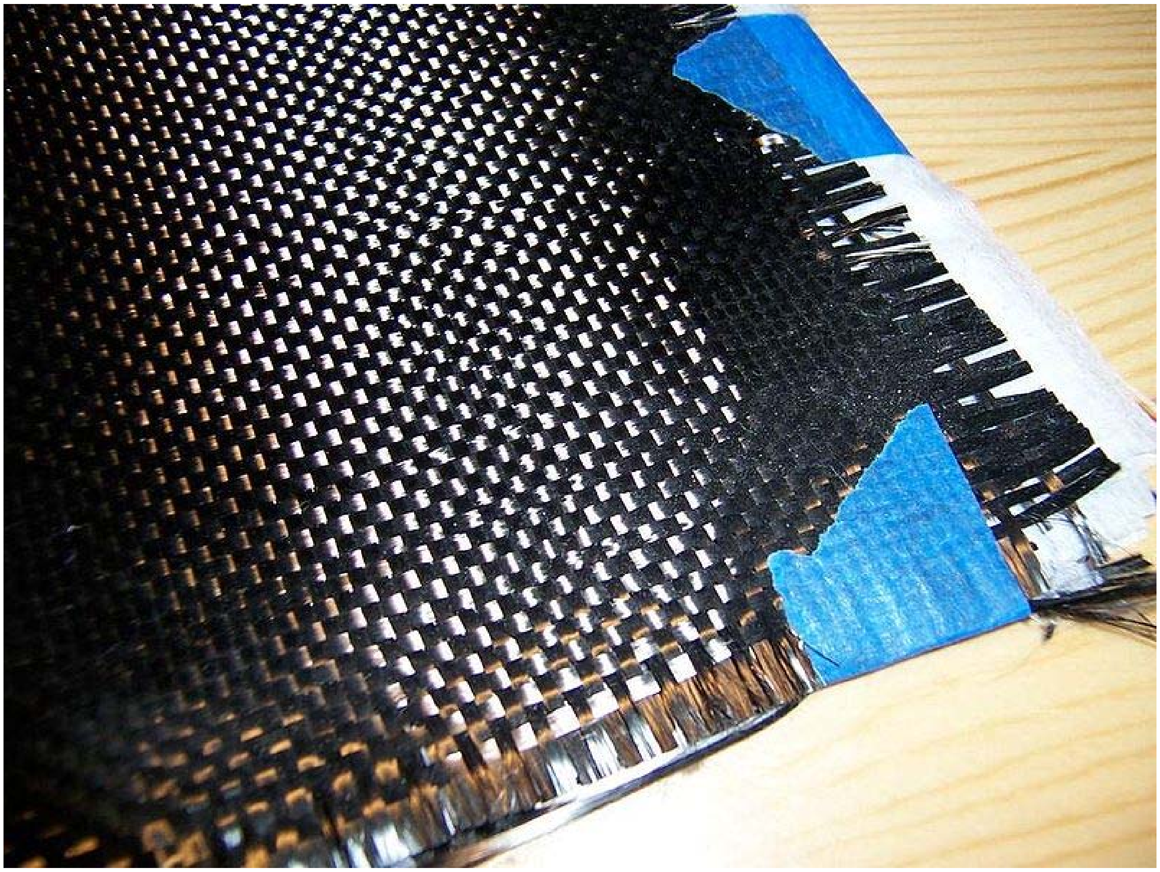
Composite Material

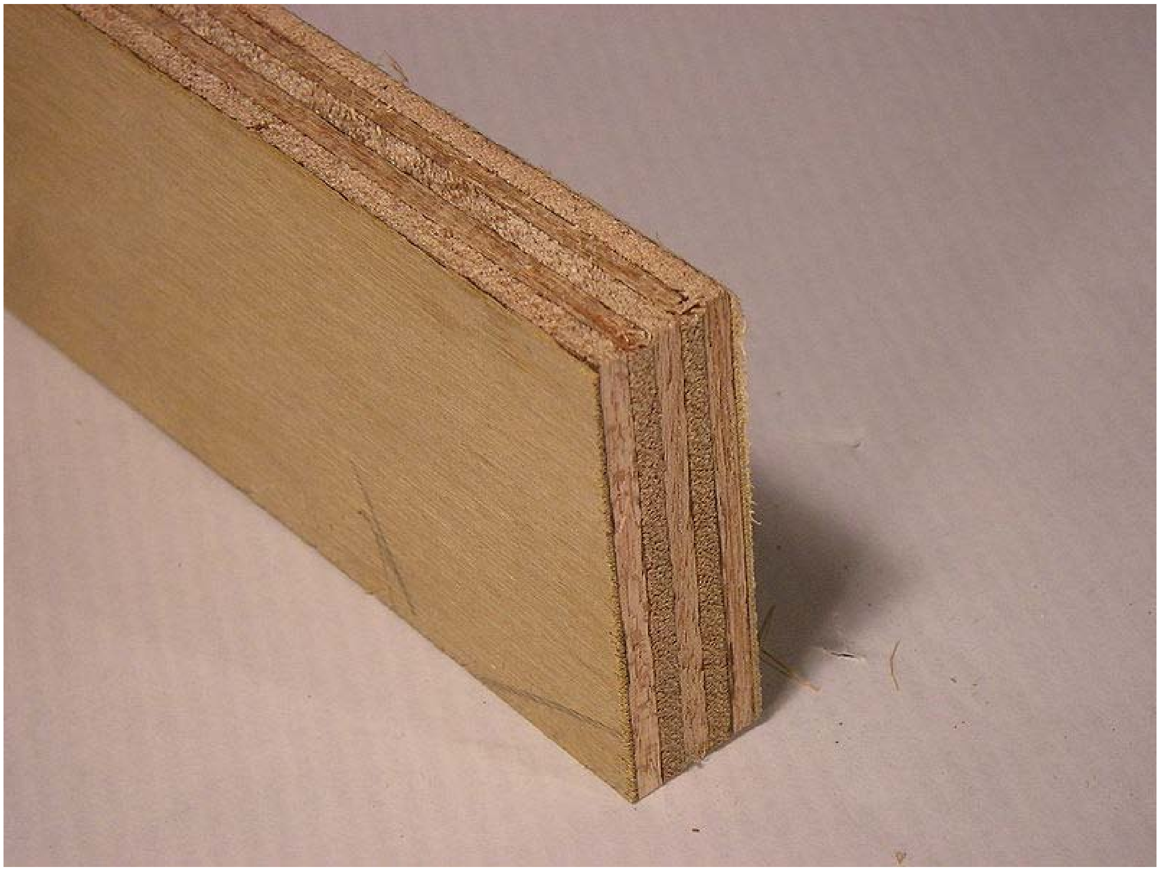


A cloth of woven carbon fiber filaments, a common element in composite materials

Composite materials, often shortened to **composites**, are engineered or naturally occurring materials made from two or more constituent materials with significantly different physical or chemical properties which remain separate and distinct at the macroscopic or microscopic scale within the finished structure.

The most visible applications is pavement in roadways in the form of either steel and aggregate reinforced Portland cement or asphalt concrete. Those composites closest to our personal hygiene form our shower stalls and bathtubs made of fibreglass. Imitation granite and cultured marble sinks and countertops are widely used. The most advanced examples perform routinely on spacecraft in demanding environments.

Composition



Plywood is a commonly encountered composite material

Wood is a natural composite of Cellulose fibers in a matrix of lignin. The earliest man-made composite materials were straw and mud combined to form bricks for building construction. The ancient brick-making process can still be seen on Egyptian tomb paintings in the Metropolitan Museum of Art.

Composites are made up of individual materials referred to as constituent materials. There are two categories of constituent materials: matrix and reinforcement. At least one portion of each type is required. The matrix material surrounds and supports the reinforcement materials by maintaining their relative positions. The reinforcements impart their special mechanical and physical properties to enhance the matrix properties. A synergism produces material properties unavailable from the individual constituent materials, while the wide variety of matrix and strengthening materials allows the designer of the product or structure to choose an optimum combination.

Engineered composite materials must be formed to shape. The matrix material can be introduced to the reinforcement before or after the reinforcement material is placed into the mould cavity or onto the mould surface. The matrix material experiences a melding event, after which the part shape is essentially set. Depending upon the nature of the matrix material, this melding event can occur in various ways such as chemical polymerization or solidification from the melted state.

A variety of moulding methods can be used according to the end-item design requirements. The principal factors impacting the methodology are the natures of the chosen matrix and reinforcement materials. Another important factor is the gross quantity of material to be produced. Large quantities can be used to justify high capital expenditures for rapid and automated manufacturing technology. Small production quantities are accommodated with lower capital expenditures but higher labour and tooling costs at a correspondingly slower rate.

Most commercially produced composites use a polymer matrix material often called a resin solution. There are many different polymers available depending upon the starting raw ingredients. There are several broad categories, each with numerous variations. The most common are known as polyester, vinyl ester, epoxy, phenolic, polyimide, polyamide, polypropylene, PEEK, and others. The reinforcement materials are often fibres but also commonly ground minerals. The various methods described below have been developed to reduce the resin content of the final product, or the fibre content is increased. As a rule of thumb, lay up results in a product containing 60% resin and 40% fibre, whereas vacuum infusion gives a final product with 40% resin and 60% fibre content. The strength of the product is greatly dependent on this ratio.

Moulding methods

In general, the reinforcing and matrix materials are combined, compacted and processed to undergo a melding event. After the melding event, the part shape is essentially set, although it can deform under certain process conditions. For a thermoset polymeric matrix material, the melding event is a curing reaction that is initiated by the application of additional heat or chemical reactivity such as an organic peroxide. For a thermoplastic polymeric matrix material, the melding event is a solidification from the melted state. For a metal matrix material such as titanium foil, the melding event is a fusing at high pressure and a temperature near the melt point.

For many moulding methods, it is convenient to refer to one mould piece as a "lower" mould and another mould piece as an "upper" mould. Lower and upper refer to the different faces of the moulded panel, not the mould's configuration in space. In this convention, there is always a lower mould, and sometimes an upper mould. Part construction begins by applying materials to the lower mould. Lower mould and upper mould are more generalized descriptors than more common and specific terms such as male side, female side, a-side, b-side, tool side, bowl, hat, mandrel, etc. Continuous manufacturing processes use a different nomenclature.

The moulded product is often referred to as a panel. For certain geometries and material combinations, it can be referred to as a casting. For certain continuous processes, it can be referred to as a profile. Applied with a pressure roller, a spray device or manually. This process is generally done at ambient temperature and atmospheric pressure. Two variations of open moulding are Hand Layup and Spray-up.

Vacuum bag moulding

A process using a two-sided mould set that shapes both surfaces of the panel. On the lower side is a rigid mould and on the upper side is a flexible membrane or vacuum bag. The flexible membrane can be a reusable silicone material or an extruded polymer film. Then, vacuum is applied to the mould cavity. This process can be performed at either ambient or elevated temperature with ambient atmospheric pressure acting upon the vacuum bag. Most economical way is using a venturi vacuum and air compressor or a vacuum pump.

A vacuum bag is a bag made of strong rubber-coated fabric or a polymer film used to bond or laminate materials. In some applications the bag encloses the entire material, or in other applications a mold is used to form one face of the laminate with the bag being single sided to seal the outer face of the laminate to the mold. The open end is sealed and the air is drawn out of the bag through a nipple using a vacuum pump. As a result, uniform pressure approaching one atmosphere is applied to the surfaces of the object inside the bag, holding parts together while the adhesive cures. The entire bag may be placed in a temperature-controlled oven, oil bath or water bath and gently heated to accelerate curing.

In commercial woodworking facilities vacuum bags are used to laminate curved and irregular shaped workpieces.

Vacuum bagging is widely used in the composites industry as well. Carbon fiber fabric and fiberglass, along with resins and epoxies are common materials laminated together with a vacuum bag operation.

Typically, polyurethane or vinyl materials are used to make the bag, which is commonly open at both ends. This gives access to the piece, or pieces to be glued. A plastic rod is laid onto the bag, which is then folded over the rod. A plastic sleeve with an opening in it, is then snapped over the rod. This procedure forms a seal at both ends of the bag, when the vacuum is ready to be drawn.

A "platen" is used inside the bag for the piece being glued to lay on. The platen has a series of small slots cut into it, to allow the air under it to be evacuated. The platen must have rounded edges and corners to prevent the vacuum from tearing the bag.

When a curved part is to be glued in a vacuum bag, it is important that the pieces being glued be placed over a solidly built form, or have an air bladder placed under the form. This air bladder has access to "free air" outside the bag. It is used to create an equal pressure under the form, preventing it from being crushed.

Pressure bag moulding

This process is related to vacuum bag moulding in exactly the same way as it sounds. A solid female mould is used along with a flexible male mould. The reinforcement is placed inside the female mould with just enough resin to allow the fabric to stick in place (wet lay up). A measured amount of resin is then liberally brushed indiscriminately into the mould and the mould is then clamped to a machine that contains the male flexible mould. The flexible male membrane is then inflated with heated compressed air or possibly steam. The female mould can also be heated. Excess resin is forced out along with trapped air. This process is extensively used in the production of composite helmets due to the lower cost of unskilled labor. Cycle times for a helmet bag moulding machine vary from 20 to 45 minutes, but the finished shells require no further curing if the moulds are heated.

Autoclave moulding

A process using a two-sided mould set that forms both surfaces of the panel. On the lower side is a rigid mould and on the upper side is a flexible membrane made from silicone or an extruded polymer film such as nylon. Reinforcement materials can be placed manually or robotically. They include continuous fibre forms fashioned into textile constructions. Most often, they are pre-impregnated with the resin in the form of prepreg fabrics or unidirectional tapes. In some instances, a resin film is placed upon the lower mould and dry reinforcement is placed above. The upper mould is installed and vacuum is applied to the mould cavity. The assembly is placed into an autoclave. This process is generally performed at both elevated pressure and elevated temperature. The use of elevated pressure facilitates a high fibre volume fraction and low void content for maximum structural efficiency.

Resin transfer moulding (RTM)

A process using a two-sided mould set that forms both surfaces of the panel. The lower side is a rigid mould. The upper side can be a rigid or flexible mould. Flexible moulds can be made from composite materials, silicone or extruded polymer films such as nylon. The two sides fit together to produce a mould cavity. The distinguishing feature of resin transfer moulding is that the reinforcement materials are placed into this cavity and the mould set is closed prior to the introduction of matrix material. Resin transfer moulding includes numerous varieties which differ in the mechanics of how the resin is introduced to the reinforcement in the mould cavity. These variations include everything from vacuum infusion to vacuum assisted resin transfer moulding (VARTM). This process can be performed at either ambient or elevated temperature.

Other

Other types of moulding include press moulding, transfer moulding, pultrusion moulding, filament winding, casting, centrifugal casting and continuous casting. There are also forming capabilities including CNC filament winding, vacuum infusion, wet lay-up, compression moulding, and thermoplastic moulding, to name a few. The use of curing ovens and paint booths is also needed for some projects.

Tooling

Some types of tooling materials used in the manufacturing of composites structures include invar, steel, aluminium, reinforced silicone rubber, nickel, and carbon fibre. Selection of the tooling material is typically based on, but not limited to, the coefficient of thermal expansion, expected number of cycles, end item tolerance, desired or required surface condition, method of cure, glass transition temperature of the material being moulded, moulding method, matrix, cost and a variety of other considerations.

Properties

Mechanics

The physical properties of composite materials are generally not isotropic (independent of direction of applied force) in nature, but rather are typically orthotropic (different depending on the direction of the applied force or load). For instance, the stiffness of a composite panel will often depend upon the orientation of the applied forces and/or moments. Panel stiffness is also dependent on the design of the panel. For instance, the fibre reinforcement and matrix used, the method of panel build, thermoset versus thermoplastic, type of weave, and orientation of fibre axis to the primary force.

In contrast, isotropic materials (for example, aluminium or steel), in standard wrought forms, typically have the same stiffness regardless of the directional orientation of the applied forces and/or moments.

The relationship between forces/moments and strains/curvatures for an isotropic material can be described with the following material properties: Young's Modulus, the shear Modulus and the Poisson's ratio, in relatively simple mathematical relationships. For the anisotropic material, it requires the mathematics of a second order tensor and up to 21 material property constants. For the special case of orthogonal isotropy, there are three different material property constants for each of Young's Modulus, Shear Modulus and Poisson's ratio—a total of 9 constants to describe the relationship between forces/moments and strains/curvatures.

Techniques that take advantage of the anisotropic properties of the materials include mortise and tenon joints (in natural composites such as wood) and Pi Joints in synthetic composites.

Resins

Typically, most common composite materials, including fiberglass, carbon fiber, and Kevlar, include at least two parts, the substrate and the resin.

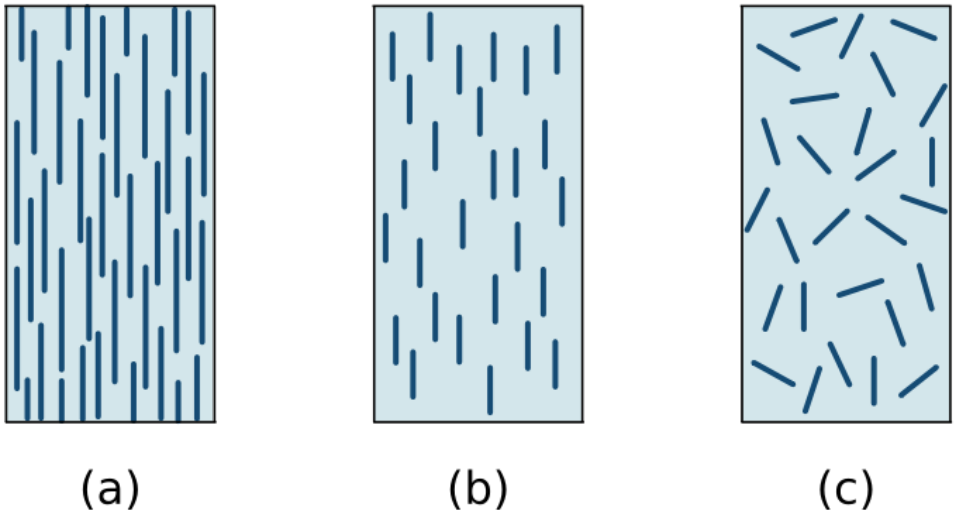
Polyester resin tends to have yellowish tint, and is suitable for most backyard projects. Its weaknesses are that it is UV sensitive and can tend to degrade over time, and thus generally is also coated to help preserve it. It is often used in the making of surfboards and for marine applications. Its hardener is a MEKP, and is mixed at 14 drops per oz. MEKP is composed of methyl ethyl ketone peroxide, a catalyst. When MEKP is mixed with the resin, the resulting chemical reaction causes heat to build up and cure or harden the resin.

Vinylester resin tends to have a purplish to bluish to greenish tint. This resin has lower viscosity than polyester resin, and is more transparent. This resin is often billed as being fuel resistant, but will melt in contact with gasoline. This resin tends to be more resistant over time to degradation than polyester resin, and is more flexible. It uses the same hardener as polyester resin (at the same mix ratio) and the cost is approximately the same.

Epoxy resin is almost totally transparent when cured. In the aerospace industry, epoxy is used as a structural matrix material or as a structural glue.

Shape memory polymer (SMP) resins have varying visual characteristics depending on their formulation. These resins may be epoxy-based, which can be used for auto body and outdoor equipment repairs; cyanate-ester-based, which are used in space applications; and acrylate-based, which can be used in very cold temperature applications, such as for sensors that indicate whether perishable goods have warmed above a certain maximum temperature. These resins are unique in that their shape can be repeatedly changed by heating above their glass transition temperature (T_g). When heated, they become flexible and elastic, allowing for easy configuration. Once they are cooled, they will maintain their new shape. The resins will return to their original shapes when they are reheated above their T_g. The advantage of shape memory polymer resins is that they can be shaped and reshaped repeatedly without losing their material properties, and these resins can be used in fabricating shape memory composites.

Categories of fiber-reinforced composite materials



Typologies of fibre-reinforced composite materials:
a) continuous fibre-reinforced
b) discontinuous aligned fibre-reinforced
c) discontinuous random-oriented fibre-reinforced.

Fiber-reinforced composite materials can be divided into two main categories normally referred to as short fiber-reinforced materials and continuous fiber-reinforced materials. Continuous reinforced materials will often constitute a layered or laminated structure. The woven and continuous fibre styles are typically available in a variety of forms, being pre-impregnated with the given matrix (resin), dry, uni-directional tapes of various widths, plain weave, harness satins, braided, and stitched.

The short and long fibers are typically employed in compression moulding and sheet moulding operations. These come in the form of flakes, chips, and random mate (which can also be made from a continuous fibre laid in random fashion until the desired thickness of the ply / laminate is achieved).

Failure

Shock, impact, or repeated cyclic stresses can cause the laminate to separate at the interface between two layers, a condition known as delamination. Individual fibres can separate from the matrix e.g. fibre pull-out.

Composites can fail on the microscopic or macroscopic scale. Compression failures can occur at both the macro scale or at each individual reinforcing fibre in compression buckling. Tension failures can be net section failures of the part or degradation of the composite at a microscopic scale where one or more of the layers in the composite fail in tension of the matrix or failure the bond between the matrix and fibres.

Some composites are brittle and have little reserve strength beyond the initial onset of failure while others may have large deformations and have reserve energy absorbing capacity past the onset of damage. The variations in fibres and matrices that are available and the mixtures that can be made with blends leave a very broad range of properties that can be designed into a composite structure. The best known failure of a brittle ceramic matrix composite occurred when the carbon-carbon composite tile on the leading edge of the wing of the Space Shuttle Columbia fractured when impacted during take-off. It led to catastrophic break-up of the vehicle when it re-entered the Earth's atmosphere on 1 February 2003.

Compared to metals, composites have relatively poor bearing strength.

Testing

To aid in predicting and preventing failures, composites are tested before and after construction. Pre-construction testing may use finite element analysis (FEA) for ply-by-ply analysis of curved surfaces and predicting wrinkling, crimping and dimpling of composites. Materials may be tested after construction through several nondestructive methods including ultrasonics, thermography, shearography and X-ray radiography

Examples

Materials

Fibre-reinforced polymers or FRPs include wood (comprising cellulose fibres in a lignin and hemicellulose matrix), carbon-fibre reinforced plastic or CFRP, and glass-reinforced plastic or GRP. If classified by matrix then there are thermoplastic composites, short fibre thermoplastics, long fibre thermoplastics or long fibre-reinforced thermoplastics. There are numerous thermoset composites, but advanced systems usually incorporate aramid fibre and carbon fibre in an epoxy resin matrix.

Shape memory polymer composites are high-performance composites, formulated using fibre or fabric reinforcement and shape memory polymer resin as the matrix. Since a shape memory polymer resin is used as the matrix, these composites have the ability to be easily manipulated into various configurations when they are heated above their activation temperatures and will exhibit high strength and stiffness at lower temperatures. They can also be reheated and reshaped repeatedly without losing their material properties. These composites are ideal for applications such as lightweight, rigid, deployable structures; rapid manufacturing; and dynamic reinforcement.

Composites can also use metal fibres reinforcing other metals, as in metal matrix composites or MMC. The benefit of magnesium is that it does not degrade in outer space. Ceramic matrix composites include bone (hydroxyapatite reinforced with collagen fibres), Cermet (ceramic and metal) and concrete. Ceramic matrix composites are built primarily for toughness, not for strength. Organic matrix/ceramic aggregate composites include asphalt concrete, mastic asphalt, mastic roller hybrid, dental composite, syntactic foam and mother of pearl. Chobham armour is a special type of composite armour used in military applications.

Additionally, thermoplastic composite materials can be formulated with specific metal powders resulting in materials with a density range from 2 g/cm³ to 11 g/cm³ (same density as lead). The most common name for this type of material is High Gravity Compound (HGC), although Lead Replacement is also used. These materials can be used in place of traditional materials such as aluminium, stainless steel, brass, bronze, copper, lead, and even tungsten in weighting, balancing (for example, modifying the centre of gravity of a tennis racquet), vibration dampening, and radiation shielding applications. High density composites are an economically viable option when certain materials are deemed hazardous and are banned (such as lead) or when secondary operations costs (such as machining, finishing, or coating) are a factor.

Engineered wood includes a wide variety of different products such as wood fibre board, plywood, oriented strand board, wood plastic composite (recycled wood fibre in polyethylene matrix), Pykrete (sawdust in ice matrix), Plastic-impregnated or laminated paper or textiles, Arborite, Formica (plastic) and Micarta. Other engineered laminate composites, such as Mallite, use a central core of end grain balsa wood, bonded to surface skins of light alloy or GRP. These generate low-weight, high rigidity materials.

Products

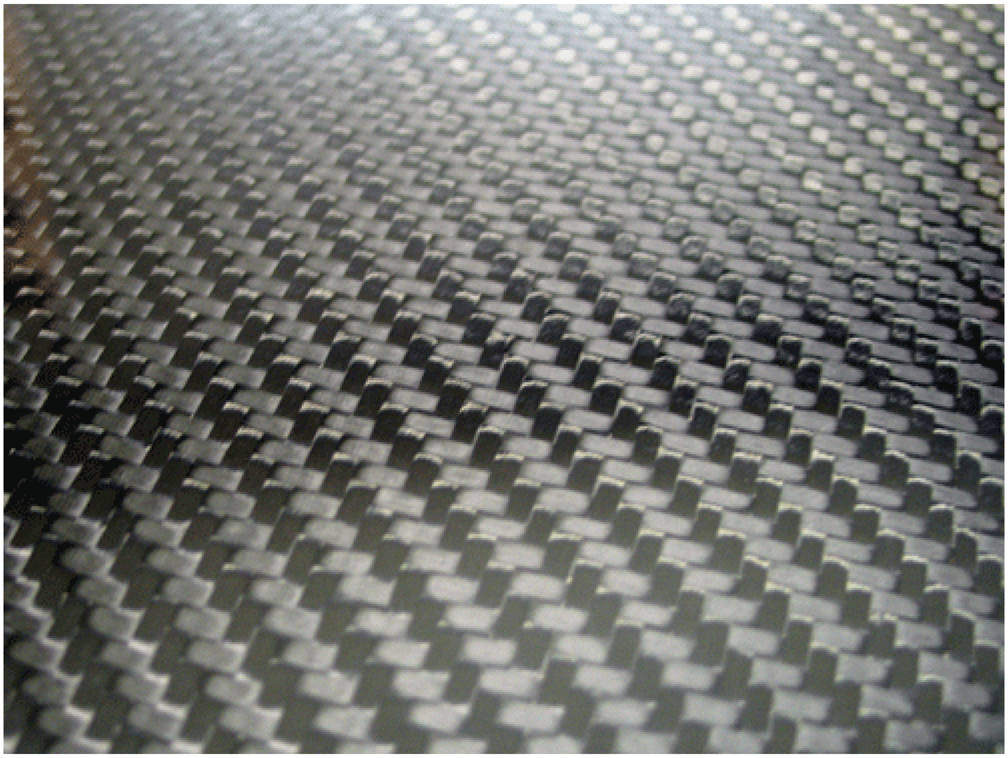
Composite materials have gained popularity (despite their generally high cost) in high-performance products that need to be lightweight, yet strong enough to take harsh loading conditions such as aerospace components (tails, wings, fuselages, propellers), boat and scull hulls, bicycle frames and racing car bodies. Other uses include fishing rods, storage tanks, and baseball bats. The new Boeing 787 structure including the wings and fuselage is composed largely of composites. Composite materials are also becoming more common in the realm of orthopedic surgery.

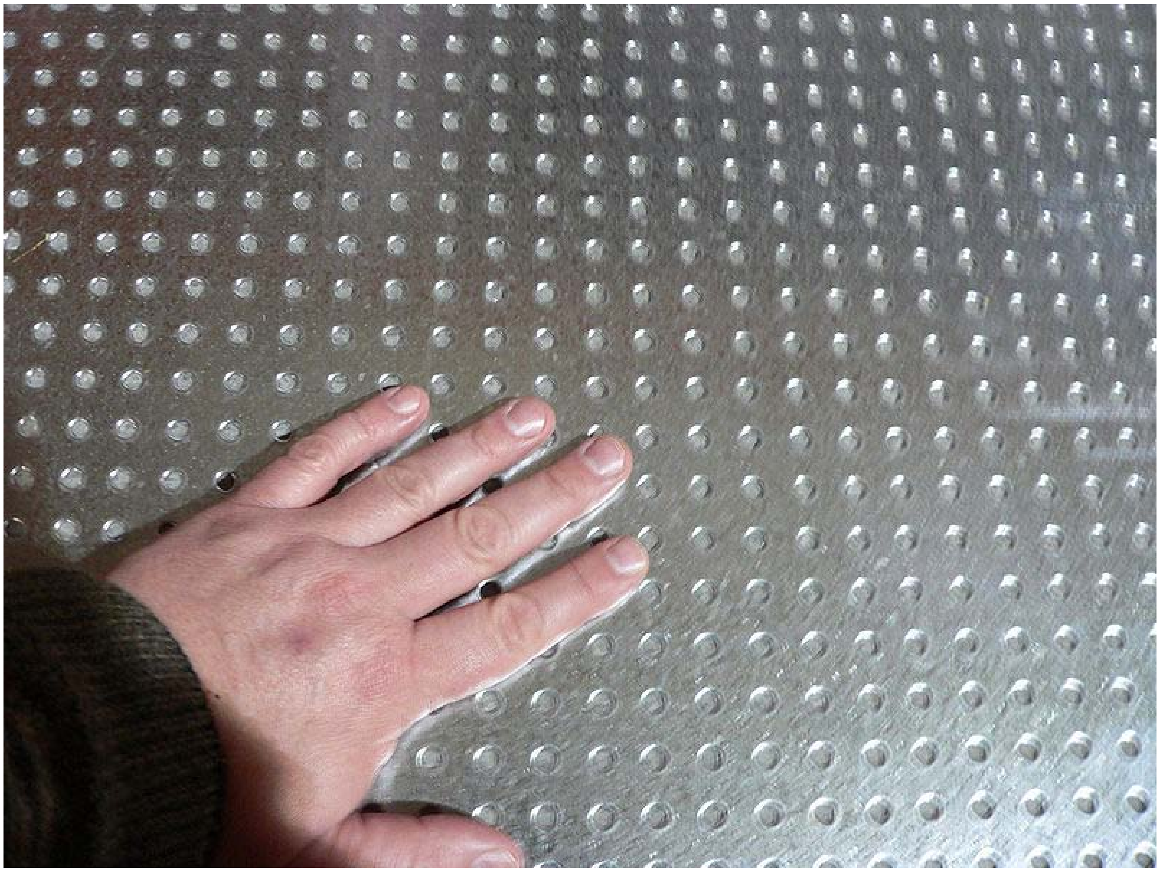
Carbon composite is a key material in today's launch vehicles and spacecraft. It is widely used in solar panel substrates, antenna reflectors and yokes of spacecraft. It is also used in payload adapters, inter-stage structures and heat shields of launch vehicles.

In 2007, an all-composite military High Mobility Multi-purpose Wheeled Vehicle (HMMWV or Hummvee) was introduced by TPI Composites Inc and Armor Holdings Inc, the first all-composite military vehicle. By using composites the vehicle is lighter, allowing higher payloads. In 2008, carbon fiber and DuPont Kevlar (five times stronger than steel) were combined with enhanced thermoset resins to make military transit cases by ECS Composites creating 30-percent lighter cases with high strength.

Many composite layup designs also include a co-curing or post-curing of the prepreg with various other mediums, such as honeycomb or foam. This is commonly called a sandwich structure. This is a more common layup process for the manufacture of radomes, doors, cowlings, or non-structural parts.

The finishing of the composite parts is also critical in the final design. Many of these finishes will include rain-erosion coatings or polyurethane coatings.





Chapter- 2

Fibre-reinforced Plastic

Fibre-reinforced plastic (**FRP**) (also *fibre-reinforced polymer*) is a composite material made of a polymer matrix reinforced with fibres. The fibres are usually fibreglass, carbon, or aramid, while the polymer is usually an epoxy, vinylester or polyester thermosetting plastic. FRPs are commonly used in the aerospace, automotive, marine, and construction industries.

Process definition

A polymer is generally manufactured by polycondensation, polymerization or polyaddition. When combined with various agents to enhance or in any way alter the material properties of polymers the result is referred to as a plastic. Composite plastics refer to those types of plastics that result from bonding two or more homogeneous materials with different material properties to derive a final product with certain desired material and mechanical properties. Fibre reinforced plastics are a category of composite plastics that specifically use fibrous materials to mechanically enhance the strength and elasticity of plastics. The original plastic material without fibre reinforcement is known as the matrix. The matrix is a tough but relatively weak plastic that is reinforced by stronger stiffer reinforcing filaments or fibres. The extent that strength and elasticity are enhanced in a fibre reinforced plastic depends on the mechanical properties of both the fibre and matrix, their volume relative to one another, and the fibre length and orientation within the matrix. Reinforcement of the matrix occurs by definition when the FRP material exhibits increased strength or elasticity relative to the strength and elasticity of the matrix alone.

History

Global polymer production on the scale present today began in the mid 20th century, when low material and productions costs, new production technologies and new product categories combined to make polymer production economical. The industry finally matured in the late 1970s when world polymer production surpassed that of Steel, making polymers the ubiquitous material that it is today. Fibre reinforced plastics have been a significant aspect of this industry from the beginning. There are three important categories of fibre used in FRP, glass, carbon, and aramid. Glass fibre reinforcement was tested in military applications at the end of World War Two, Carbon fibre production began in the late 1950s and was used, though not widely, in British industry beginning in the early 1960s, aramid fibres were being produced around this time also, appearing first under the trade name Nomex by DuPont. Today each of these fibres is used widely in industry for any applications that require plastics with specific strength or elastic qualities. Glass fibres are the most common across all industries, although carbon fibre and carbon fibre aramid composites are widely found in aerospace, automotive and sporting good applications.

Process description

FRP involves two distinct processes, the first is the process whereby the fibrous material is manufactured and formed, the second is the process whereby fibrous materials are bonded with the matrix during the moulding process.

Fibre process

The manufacture of fibre fabric

Reinforcing Fibre is manufactured in both two dimensional and three dimensional orientations

1. Two Dimensional Fibre Reinforced Polymer are characterized by a laminated structure in which the fibres are only aligned along the plane in x-direction and y-direction of the material. This means that no fibres are aligned in the through thickness or the z-direction, this lack of alignment in the through thickness can create a disadvantage in cost and processing. Costs and labour increase because conventional processing techniques used to fabricate composites, such as wet hand lay-up, autoclave and resin transfer moulding, require a high amount of skilled labour to cut, stack and consolidate into a preformed component.
2. Three-dimensional Fibre Reinforced Polymer composites are materials with three dimensional fibre structures that incorporate fibres in the x-direction, y-direction and z-direction. The development of three-dimensional orientations arose from industry's need to reduce fabrication costs, to increase through-thickness mechanical properties, and to improve impact damage tolerance; all were problems associated with two dimensional fibre reinforced polymers.

The manufacture of fibre preforms

Fiber preforms are how the fibres are manufactured before being bonded to the matrix. Fibre preforms are often manufactured in sheets, continuous mats, or as continuous filaments for spray applications. The four major ways to manufacture the fibre preform is though the textile processing techniques of Weaving, knitting, braiding and stitching.

1. Weaving can be done in a conventional manner to produce two-dimensional fibres as well in a multilayer weaving that can create three-dimensional fibres. However multilayer weaving is required to have multiple layers of warp yarns to create fibres in the z- direction creating a few disadvantages in

manufacturing,namely the time to set up all the warp yarns on the loom. Therefore most multilayer weaving is currently used to produce relatively narrow width products, or high value products where the cost of the preform production is acceptable. Another one of the main problems facing the use of multilayer woven fabrics is the difficulty in producing a fabric that contains fibres oriented with angles other than 0" and 90" to each other respectively.

2. The second major way of manufacturing fibre preforms is Braiding. Braiding is suited to the manufacture of narrow width flat or tubular fabric and is not as capable as weaving in the production of large volumes of wide fabrics. Braiding is done over top of mandrels that vary in cross-sectional shape or dimension along their length. Braiding is limited to objects about a brick in size. Unlike the standard weaving process, braiding can produce fabric that contains fibres at 45 degrees angles to one another. Braiding three-dimensional fibres can be done using four step, two-step or Multilayer Interlock Braiding.Four step or row and column braiding utilizes a flat bed containing rows and columns of yarn carriers that form the shape of the desired preform. Additional carriers are added to the outside of the array, the precise location and quantity of which depends upon the exact preform shape and structure required. There are four separate sequences of row and column motion, which act to interlock the yarns and produce the braided preform. The yarns are mechanically forced into the structure between each step to consolidate the structure in a similar process to the use of a reed in weaving.Two-step braiding is unlike the four step process because the two-step includes a large number of yarns fixed in the axial direction and a fewer number of braiding yarns. The process consists of two steps in which the braiding carriers move completely through the structure between the axial carriers. This relatively simple sequence of motions is capable of forming preforms of essentially any shape, including circular and hollow shapes. Unlike the four step process the two step process does not require mechanical compaction the motions involved in the process allows the braid to be pulled tight by yarn tension alone. The last type of braiding is multi-layer interlocking braiding that consists of a number of standard circular braiders being joined together to form a cylindrical braiding frame. This frame has a number of parallel braiding tracks around the circumference of the cylinder but the mechanism allows the transfer of yarn carriers between adjacent tracks forming a multilayer braided fabric with yarns interlocking to adjacent layers. The multilayer interlock braid differs from both the four step and two-step braids in that the interlocking yarns are primarily in the plane of the structure and thus do not significantly reduce the in-plane properties of the preform. The four step and two step processes produce a greater degree of interlinking as the braiding yarns travel through the thickness of the preform, but therefore contribute less to the in-plane performance of the preform. A disadvantage of the multilayer interlock equipment is that due to the conventional sinusoidal movement of the yarn carriers to form the preform, the equipment is not able to have the density of yarn carriers that is possible with the two step and four step machines.
3. Knitting fibre preforms can be done with the traditional methods of Warp and [Weft] Knitting, and the fabric produced is often regarded by many as two-

dimensional fabric, but machines with two or more needle beds are capable of producing multilayer fabrics with yams that traverse between the layers. Developments in electronic controls for needle selection and knit loop transfer, and in the sophisticated mechanisms that allow specific areas of the fabric to be held and their movement controlled. This has allowed the fabric to form itself into the required three-dimensional preform shape with a minimum of material wastage.

4. Stitching is arguably the simplest of the four main textile manufacturing techniques and one that can be performed with the smallest investment in specialized machinery. Basically the stitching process consists of inserting a needle, carrying the stitch thread, through a stack of fabric layers to form a 3D structure. The advantages of stitching are that it is possible to stitch both dry and prepreg fabric, although the tackiness of the prepreg makes the process difficult and generally creates more damage within the prepreg material than in the dry fabric. Stitching also utilizes the standard two-dimensional fabrics that are commonly in use within the composite industry therefore there is a sense of familiarity concerning the material systems. The use of standard fabric also allows a greater degree of flexibility in the fabric lay-up of the component than is possible with the other textile processes, which have restrictions on the fibre orientations that can be produced.

Moulding processes

There are two distinct categories of moulding processes using FRP plastics; this includes composite moulding and wet moulding. Composite moulding uses Prepreg FRP, meaning the plastics are fibre reinforced before being put through further the moulding process. Sheets of Prepreg FRP are heated or compressed in different ways to create geometric shapes. Wet moulding combines fibre reinforcement and the matrix or resist during the moulding process. The different forms of composite and wet moulding, are listed below.

Composite moulding

Bladder moulding

Individual sheets of prepreg material are laid -up and placed in a female-style mould along with a balloon-like bladder. The mould is closed and placed in a heated press. Finally, the bladder is pressurized forcing the layers of material against the mould walls. The part is cured and removed from the hot mould. Bladder moulding is a closed moulding process with a relatively short cure cycle between 15 and 60 minutes making it ideal for making complex hollow geometric shapes at competitive costs.

Compression moulding

A "preform" or "charge", of SMC, BMC or sometimes prepreg fabric, is placed into mould cavity. The mould is closed and the material is compacted & cured inside by pressure and heat. Compression moulding offers excellent detailing for geometric shapes ranging from pattern and relief detailing to complex curves and creative forms, to precision engineering all within a maximum curing time of 20 minutes.

Autoclave / vacuum bag

Individual sheets of prepreg material are laid-up and placed in an open mold. The material is covered with release film, bleeder/breather material and a vacuum bag. A vacuum is pulled on part and the entire mould is placed into an autoclave (heated pressure vessel). The part is cured with a continuous vacuum to extract entrapped gasses from laminate. This is a very common process in the aerospace industry because it affords precise control over the moulding process due to a long slow cure cycle that is anywhere from one to two hours. This precise control creates the exact laminate geometric forms needed to ensure strength and safety in the aerospace industry, but it is also slow and labour intensive, meaning costs often confine it to the aerospace industry.

Mandrel wrapping

Sheets of prepreg material are wrapped around a steel or aluminium mandrel. The prepreg material is compacted by nylon or polypropylene cello tape. Parts are typically batch cured by hanging in an oven. After cure the cello and mandrel are removed leaving a hollow carbon tube. This process creates strong and robust hollow carbon tubes.

Wet layup

Fibre reinforcing fabric is placed in an open mould and then saturated with a wet [resin] by pouring it over the fabric and working it into the fabric and mould. The mould is then left so that the resin will cure, usually at room temperature, though heat is sometimes used to ensure a proper curing process. Glass fibres are most commonly used for this process, the results are widely known as fibreglass, and is used to make common products like skis, canoes, kayaks and surf boards.

Chopper gun

Continuous strand of fibreglass are pushed through a hand-held gun that both chops the strands and combines them with a catalyzed resin such as polyester. The impregnated chopped glass is shot onto the mould surface in whatever thickness the design and human operator think is appropriate. This process is good for large production runs at economical cost, but produces geometric shapes with less strength then other moulding processes and has poor dimensional tolerance.

Filament winding

Machines pull fibre bundles through a wet bath of resin and wound over a rotating steel mandrel in specific orientations Parts are cured either room temperature or elevated temperatures. Mandrel is extracted, leaving a final geometric shape but can be left in some cases.

Pultrusion

Fibre bundles and slit fabrics are pulled through a wet bath of resin and formed into the rough part shape. Saturated material is extruded from a heated closed die curing while being continuously pulled through die. Some of the end products of the pultrusion process are structural shapes, i.e. I beam, angle, channel and flat sheet. These materials can be used to create all sorts of fibreglass structures such as ladders, platforms, handrail systems tank, pipe and pump supports.

RTM & VARTM

Fabrics are placed into a mould which wet resin is then injected into. Resin is typically pressurized and forced into a cavity which is under vacuum in the RTM process. Resin is entirely pulled into cavity under vacuum in the VARTM process. This moulding process allows precise tolerances and detailed shaping but can sometimes fail to fully saturate the fabric leading to weak spots in the final shape.

Advantages and limitations

FRP allows the alignment of the glass fibres of thermoplastics to suit specific design programs. Specifying the orientation of reinforcing fibres can increase the strength and resistance to deformation of the polymer. Glass reinforced polymers are strongest and most resistive to deforming forces when the polymers fibres are parallel to the force being exerted, and are weakest when the fibres are perpendicular. Thus this ability is at once both an advantage or a limitation depending on the context of use. Weak spots of perpendicular fibres can be used for natural hinges and connections, but can also lead to material failure when production processes fail to properly orient the fibres parallel to expected forces. When forces are exerted perpendicular to the orientation of fibres the strength and elasticity of the polymer is less than the matrix alone. In cast resin components made of glass reinforced polymers such as UP and EP, the orientation of fibres can be oriented in two-dimensional and three-dimensional weaves. This means that when forces are possibly perpendicular to one orientation, they are parallel to another orientation; this eliminates the potential for weak spots in the polymer.

Failure modes

Structural failure can occur in FRP materials when:

- Tensile forces stretch the matrix more than the fibres, causing the material to shear at the interface between matrix and fibres.
- Tensile forces near the end of the fibres exceed the tolerances of the matrix, separating the fibres from the matrix.
- Tensile forces can also exceed the tolerances of the fibres causing the fibres themselves to fracture leading to material failure.

Material requirements

The matrix must also meet certain requirements in order to first be suitable for the FRP process and ensure a successful reinforcement of itself. The matrix must be able to properly saturate, and bond with the fibres within a suitable curing period. The matrix should preferably bond chemically with the fibre reinforcement for maximum adhesion. The matrix must also completely envelope the fibres to protect them from cuts and notches that would reduce their strength, and to transfer forces to the fibres. The fibres must also be kept separate from each other so that if failure occurs it is localized as much as possible, and if failure occurs the matrix must also debond from the fibre for similar reasons. Finally the matrix should be of a plastic that remains chemically and physically stable during and after reinforcement and moulding processes. To be suitable for reinforcement material fibre additives must increase the tensile strength and modulus of elasticity of the matrix and meet the following conditions; fibres must exceed critical fibre content; the strength and rigidity of fibres itself must exceed the strength and rigidity of the matrix alone; and there must be optimum bonding between fibres and matrix

Glass fibre material

FRP plastics use textile glass fibres; textile fibres are different from other forms of glass fibres used for insulating applications. Textile glass fibres begin as varying combinations of SiO_2, Al_2O_3, B_2O_3, CaO, or MgO in powder form. These mixtures are then heated through a direct melt process to temperatures around 1300 degrees Celsius, after which dies are used to extrude filaments of glass fibre in diameter ranging from 9 to 17 µm. These filaments are then wound into larger threads and spun onto bobbins for transportation and further processing. Glass fibre is by far the most popular means to reinforce plastic and thus enjoys a wealth of production processes, some of which are applicable to aramid and carbon fibres as well owing to their shared fibrous qualities.

Glass fibre material processes

Roving

Process where filaments are spun into larger diameter threads. These threads are then commonly used for woven reinforcing glass fabrics and mats, and in spray applications.

Fibre fabric

Web-form fabric reinforcing material that has both warp and weft directions

Fibre mats

Web-form non-woven mats of glass fibres. Mats are manufactured in cut dimensions with chopped fibres, or in continuous mats using continuous fibres.

Chopped fibre glass

Processes where lengths of glass threads are cut between 3 and 26 mm, threads are then used in plastics most commonly intended for moulding processes.

Glass fibre short strands

Short 0.2–0.3 mm strands of glass fibres that are used to reinforce thermoplastics most commonly for injection moulding.

Carbon fibre

Carbon fibres are created when polyacrylonitrile fibres (PAN), Pitch resins, or Rayon are carbonized (through oxidation and thermal pyrolysis) at high temperatures. Through further processes of graphitizing or stretching the fibres strength or elasticity can be enhanced respectively. Carbon fibres are manufactured in diameters analogous to glass fibres with diameters ranging from 9 to 17 µm. These fibres wound into larger threads for transportation and further production processes. Further production processes include weaving or braiding into carbon fabrics, cloths and mats analogous to those described for glass that can then be used in actual reinforcement processes.

Aramid fibre material process

Aramid fibres are most commonly known Kevlar, Nomex and Technora. Aramids are generally prepared by the reaction between an amine group and a carboxylic acid halide group (aramid) ; commonly this occurs when an aromatic polyamide is spun from a liquid concentration of sulfuric acid into a crystallized fibre. Fibres are then spun into larger threads in order to weave into large ropes or woven fabrics (Aramid). Aramid fibres are manufactured with varying grades to based on varying qualities for strength and rigidity, so that the material can be somewhat tailored to specific design needs concerns, such as cutting the tough material during manufacture.

Examples of polymers best suited for the process

Reinforcing Material	Most Common Matrix Materials	Properties Improved
Glass Fibres	UP, EP, PA, PC, POM, PP, PBT, VE	Strength, Elastic, heat resistance
Carbon and Aramid Fibres	EP, UP, VE, PA	Elasticity, Tensile Strength
Inorganic Particulates	Semicrystalline Thermoplastics, UP	Isotropic shrinkage, abrasion, compression strength

Applications

Fibre-reinforced plastics are best suited for any design program that demands weight savings, precision engineering, finite tolerances, and the simplification of parts in both production and operation. A moulded polymer artefact is cheaper, faster, and easier to manufacture than cast aluminium or steel artefact, and maintains similar and sometimes better tolerances and material strengths. The Mitsubishi Lancer Evolution IV also used FRP for its spoiler material.

Carbon fibre reinforced polymers

Rudder of A310 Airbus

- Advantages over a traditional rudder made from sheet aluminium are:
    - 25% reduction in weight
    - 95% reduction in components by combining parts and forms into simpler moulded parts.
    - Overall reduction in production and operational costs, economy of parts results in lower production costs and the weight savings create fuel savings that lower the operational costs of flying the aeroplane.

Structural Applications of FRP

FRP can be applied to strengthen the beams, columns and slabs in buildings. It is possible to increase strength of these structural members even after these have been severely damaged due to loading conditions.

For strengthening beams, two techniques are adopted. First one is to paste FRP plates to the bottom (generally the tension face)of a beam. This increases the strength of beam, deflection capacity of beam and stiffness (load required to make unit deflection). Alternately, FRP strips can be pasted in 'U' shape around the sides and bottom of a beam, resulting in higher shear resistance.

Columns in building can be wrapped with FRP for achieving higher strength. This is called wrapping of columns. The technique works by restraining the lateral expansion of the column.

Slabs may be strengthened by pasting FRP strips at their bottom (tension face). This will result in better performance, since the tensile resistance of slabs is supplemented by the tensile strength of FRP.

In the case of beams and slabs, the effectiveness of FRP strengthening depends on the performance of the resin chosen for bonding.

===Glass fibre reinforced polymers or concrete Engine intake manifolds are made from glass fibre reinforced PA 66.

- Advantages this has over caste aluminium manifolds are:
    - Up to a 60% reduction in weight
    - Improved surface quality and aerodynamics
    - Reduction in components by combining parts and forms into simpler molded shapes.

Automotive gas and clutch pedals made from glass fibre reinforced PA 66 (DWP 12-13)

- Advantages over stamped aluminium are:
    - Pedals can be moulded as single units combining both pedals and mechanical linkages simplifying the production and operation of the design.
    - Fibres can be oriented to reinforce against specific stresses, increasing the durability and safety.

Design considerations

FRP is used in designs that require a measure of strength or modulus of elasticity that non-reinforced plastics and other material choices are either ill suited for mechanically or economically. This means that the primary design consideration for using FRP is to ensure that the material is used economically and in a manner that takes advantage of its structural enhancements specifically. This is however not always the case, the orientation of fibres also creates a material weakness perpendicular to the fibres. Thus the use of fibre reinforcement and their orientation affects the strength, rigidity, and elasticity of a final form and hence the operation of the final product itself. Orienting the direction of fibres either, unidirectional, 2-dimensionally, or 3-dimensionally during production affects the degree of strength, flexibility, and elasticity of the final product. Fibres oriented in the direction of forces display greater resistance to distortion from these forces and vice versa, thus areas of a product that must withstand forces will be reinforced with fibres in the same direction, and areas that require flexibility, such as natural hinges, will use fibres in a perpendicular direction to forces. Using more dimensions avoids this either or scenario and creates objects that seek to avoid any specific weak points due to the unidirectional orientation of fibres. The properties of strength, flexibility and elasticity can also be magnified or diminished through the geometric shape and design of the final product. These include such design consideration such as ensuring proper wall thickness and creating multifunctional geometric shapes that can be moulding as single pieces, creating shapes that have more material and structural integrity by reducing joints, connections, and hardware.

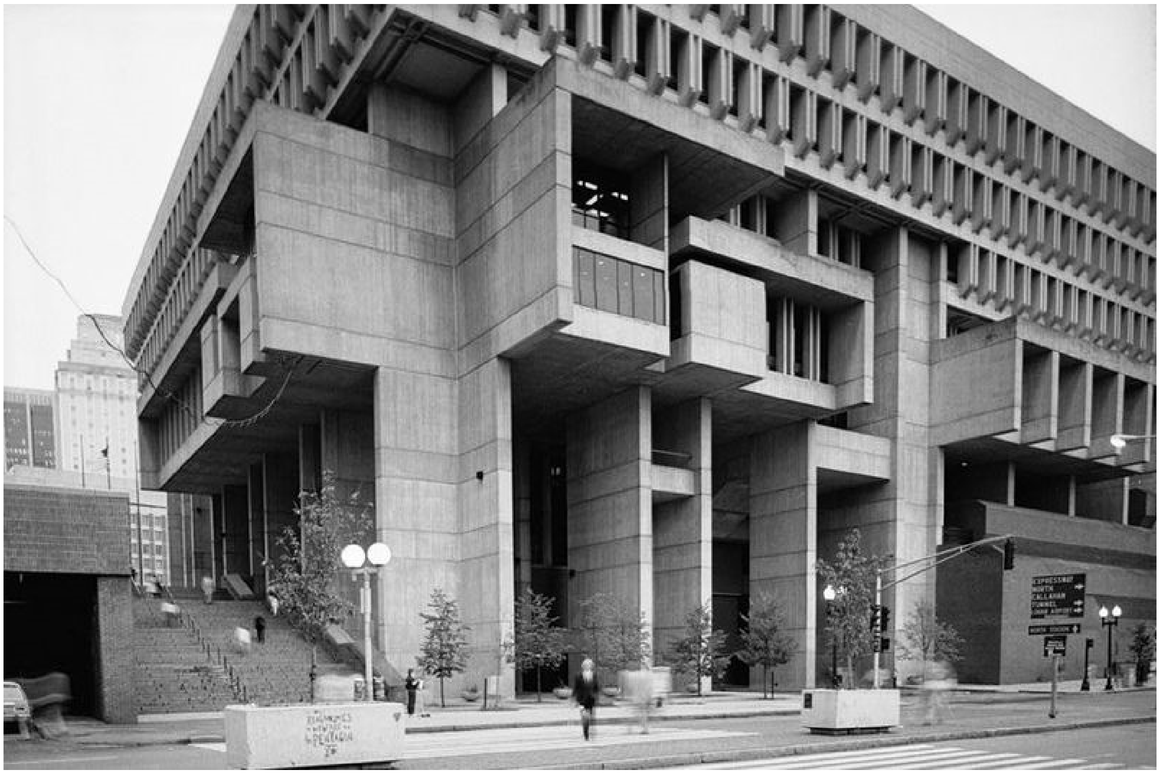
Disposal and recycling concerns

As a subset of plastic FRP plastics are liable to a number of the issues and concerns in plastic waste disposal and recycling. Plastics pose a particular challenge in recycling processes because they are derived from polymers and monomers that often cannot be separated and returned to their virgin states, for this reason not all plastics can be recycled for re-use, in fact some estimates claim only 20% to 30% of plastics can be material recycled at all. Fibre reinforced plastics and their matrices share these disposal and environmental concerns. In addition to these concerns, the fact that the fibres themselves are difficult to remove from the matrix and preserve for re-use means FRP amplify these challenges. FRP are inherently difficult to separate into base a material, that is into fibre and matrix, and the matrix into separate usable plastic, polymers, and monomers. These are all concerns for environmentally informed design today, but it must be noted that plastics often offer savings in energy and economic savings in comparison to other materials, also with the advent of new more environmentally friendly matrices such as bioplastics and uv-degradable plastics, FRP will similarly gain environmental sensitivity.

Chapter- 3

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: $2Ca_3SiO_5 + 7H_2O \rightarrow 3(CaO)\cdot 2(SiO_2)\cdot 4(H_2O)(gel) + 3Ca(OH)_2$

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 $CaCl_2$ and NaCl. However, use of chlorides may cause corrosion in steel reinforcing and is prohibited in some countries.
- 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

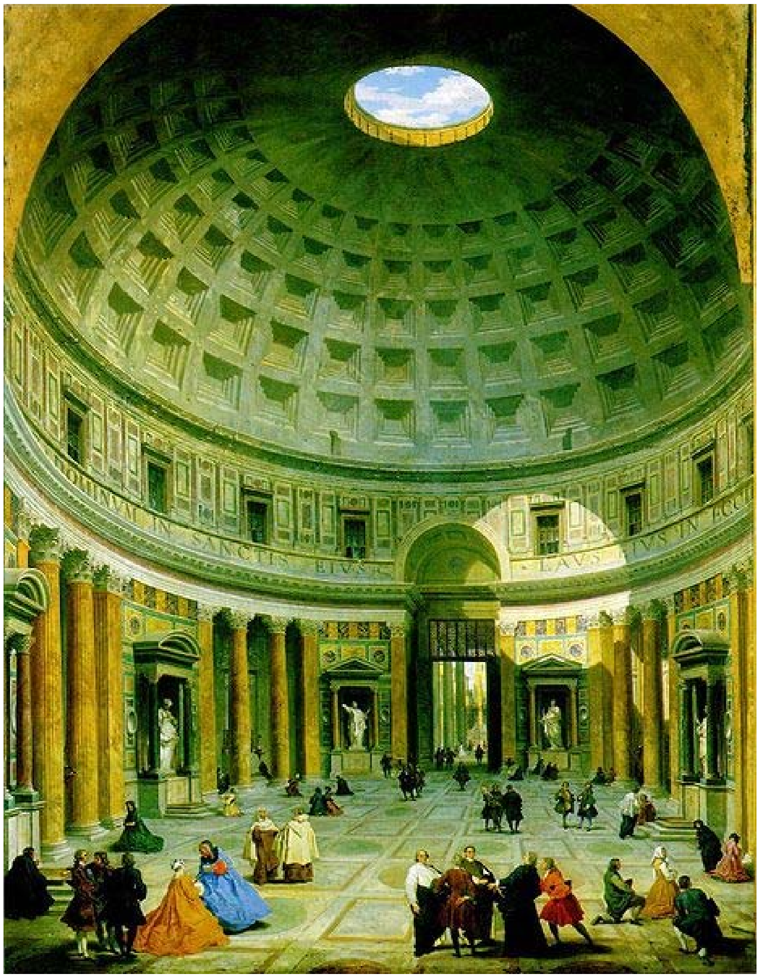
The world record was set at on 7 August 2009 during the construction of the Parbati Hydroelectric Project, near the village of Suind, Himachal Pradesh, India, when the concrete mix was pumped through a vertical height of 715 m (2,346 ft).

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

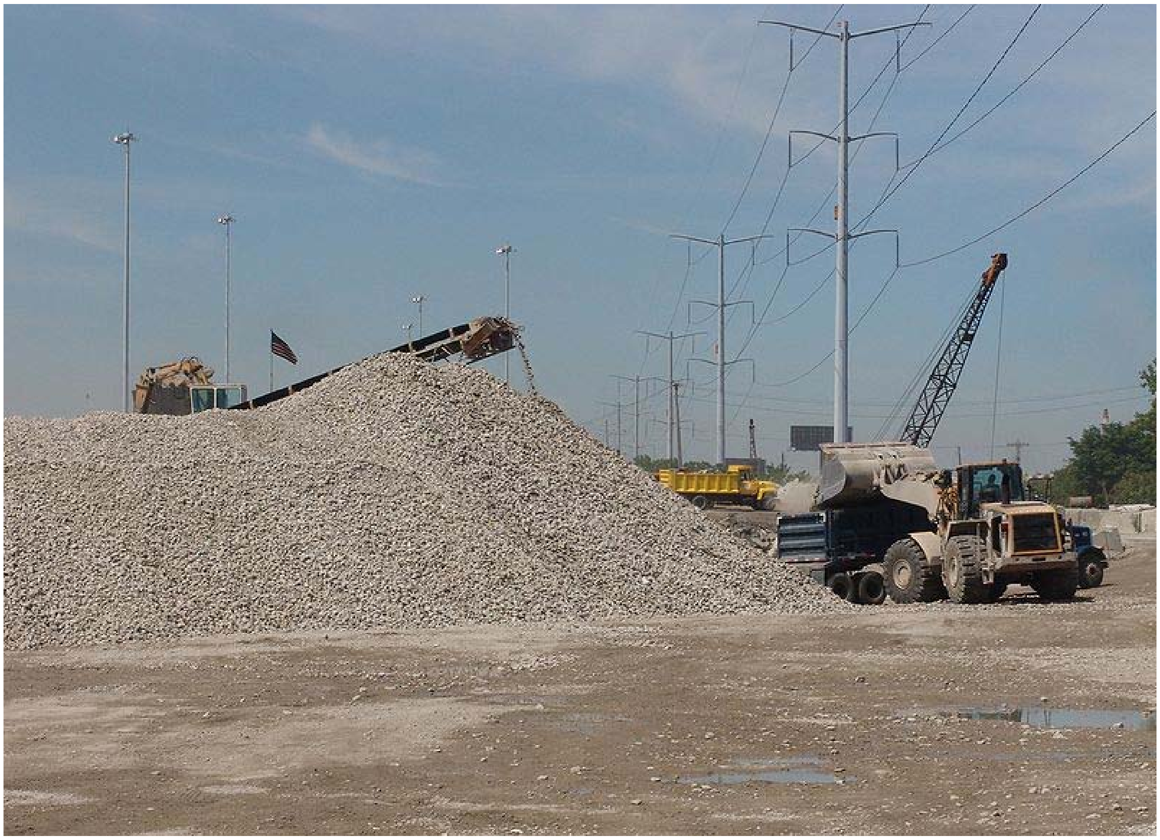
- among the burned houses, 50% of those made with wood had to be demolished, whereas only 9% of the concrete ones were beyond repair
- the fire spread to neighbouring apartments in only three of the 55 fires in concrete houses
- of those 55 fires, 45 were in attics and roofing

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- 4

Carbon Fiber-reinforced Polymer

Tail of an RC helicopter, made of CFRP

Carbon fiber-reinforced polymer or **carbon fiber-reinforced plastic** (**CFRP** or **CRP**), is a very strong, light, and expensive composite material or fiber-reinforced polymer. Similar to fiberglass (glass reinforced polymer), the composite material is commonly referred to by the name of its reinforcing fibers (carbon fiber). The polymer is most often epoxy, but other polymers, such as polyester, vinyl ester or nylon, are sometimes used. Some composites contain both carbon fiber and other fibers such as Kevlar, aluminium, and fiberglass reinforcement. The terms **graphite-reinforced polymer** or **graphite fiber-reinforced polymer** (**GFRP**) are also used, but less commonly, since glass-(fiber)-reinforced polymer can also be called GFRP. In product advertisements, it is sometimes referred to simply as **graphite fiber** (or **graphite fibre**), for short.

It has many applications in aerospace and automotive fields, as well as in sailboats, and notably in modern bicycles and motorcycles, where its high strength-to-weight ratio is of importance. Improved manufacturing techniques are reducing the costs and time to manufacture, making it increasingly common in small consumer goods as well, such as laptops, tripods, fishing rods, paintball equipment, archery equipment, racquet frames, stringed instrument bodies, classical guitar strings, drum shells, golf clubs, and pool/billiards/snooker cues.

Composite

Materials produced with the above-mentioned methodology are often generically referred to as *composites*. The choice of matrix can have a profound effect on the properties of the finished composite. One method of producing graphite-epoxy parts is by layering sheets of carbon fiber cloth into a mold in the shape of the final product. The alignment and weave of the cloth fibers is chosen to optimize the strength and stiffness properties of the resulting material. The mold is then filled with epoxy and is heated or air-cured. The resulting part is very corrosion-resistant, stiff, and strong for its weight. Parts used in less critical areas are manufactured by draping cloth over a mold, with epoxy either preimpregnated into the fibers (also known as *prepreg*) or "painted" over it. High-performance parts using single molds are often vacuum-bagged and/or autoclave-cured, because even small air bubbles in the material will reduce strength.

Process

The process by which most carbon fiber-reinforced polymer is made varies, depending on the piece being created, the finish (outside gloss) required, and how many of this particular piece are going to be produced.

For simple pieces of which relatively few copies are needed, (1–2 per day) a vacuum bag can be used. A fiberglass, carbon fiber or aluminum mold is polished and waxed, and has a release agent applied before the fabric and resin are applied, and the vacuum is pulled and set aside to allow the piece to cure (harden). There are two ways to apply the resin to the fabric in a vacuum mold. One is called a wet layup, where the two-part resin is mixed and applied before being laid in the mold and placed in the bag. The other is a resin induction system, where the dry fabric and mold are placed inside the bag while the vacuum pulls the resin through a small tube into the bag, then through a tube with holes or something similar to evenly spread the resin throughout the fabric. Wire loom works perfectly for a tube that requires holes inside the bag. Both of these methods of applying resin require hand work to spread the resin evenly for a glossy finish with very small pinholes. A third method of constructing composite materials is known as a dry layup. Here, the carbon fiber material is already impregnated with resin (prepreg) and is applied to the mold in a similar fashion to adhesive film. The assembly is then placed in a vacuum to cure. The dry layup method has the least amount of resin waste and can achieve lighter constructions than wet layup. Also, because larger amounts of resin are more difficult to bleed out with wet layup methods, prepreg parts generally have fewer pinholes. Pinhole elimination with minimal resin amounts generally require the use of autoclave pressures to purge the residual gases out.

A quicker method uses a compression mold. This is a two-piece (male and female) mold usually made out of fiberglass or aluminum that is bolted together with the fabric and resin between the two. The benefit is that, once it is bolted together, it is relatively clean and can be moved around or stored without a vacuum until after curing. However, the molds require a lot of material to hold together through many uses under that pressure.

Many carbon fiber-reinforced polymer parts are created with a single layer of carbon fabric, and filled with fiberglass. A tool called a chopper gun can be used to quickly create these types of parts. Once a thin shell is created out of carbon fiber, the chopper gun is a pneumatic tool that cuts fiberglass from a roll and sprays resin at the same time, so that the fiberglass and resin are mixed on the spot. The resin is either external mix, wherein the hardener and resin are sprayed separately, or internal, where they are mixed internally, which requires cleaning after every use.

For difficult or convoluted shapes, a filament winder can be used to make pieces.

Automotive uses

Carbon fiber-reinforced polymer is used extensively in high-end automobile racing. The high cost of carbon fiber is mitigated by the material's unsurpassed strength-to-weight ratio, and low weight is essential for high-performance automobile racing. Racecar manufacturers have also developed methods to give carbon fiber pieces strength in a certain direction, making it strong in a load-bearing direction, but weak in directions where little or no load would be placed on the member. Conversely, manufacturers developed omnidirectional carbon fiber weaves that apply strength in all directions. This type of carbon fiber assembly is most widely used in the "safety cell" monocoque chassis assembly of high-performance racecars.

Many supercars over the past few decades have incorporated CFRP extensively in their manufacture, using it for their monocoque chassis as well as other components.

Until recently, the material has had limited use in mass-produced cars because of the expense involved in terms of materials, equipment, and the relatively limited pool of individuals with expertise in working with it. Recently, several mainstream vehicle manufacturers have started to use CFRP in everyday road cars.

Use of the material has been more readily adopted by low-volume manufacturers who used it primarily for creating body-panels for some of their high-end cars due to its increased strength and decreased weight compared with the glass-reinforced polymer they used for the majority of their products.

Civil engineering applications

Carbon fiber reinforced polymer-[CFRP] has over the past two decades become an increasingly notable material used in structural engineering applications. Studied in an academic context as to its potential benefits in construction, it has also proved itself cost-effective in a number of field applications strengthening concrete, masonry, steel, cast iron, and timber structures. Its use in industry can be either for retrofitting to strengthen an existing structure or as an alternative reinforcing (or prestressing material) instead of steel from the outset of a project.

Retrofitting has become the increasingly dominant use of the material in civil engineering, and applications include increasing the load capacity of old structures (such as bridges) that were designed to tolerate far lower service loads than they are experiencing today, seismic retrofitting, and repair of damaged structures. Retrofitting is popular in many instances as the cost of replacing the deficient structure can greatly exceed its strengthening using CFRP.

Applied to reinforced concrete structures for flexure, CFRP typically has a large impact on strength (doubling or more the strength of the section is not uncommon), but only a moderate increase in stiffness (perhaps a 10% increase). This is because the material used in this application is typically very strong (e.g., 3000 MPa ultimate tensile strength, more than 10 times mild steel) but not particularly stiff (150 to 250 GPa, a little less than steel, is typical). As a consequence, only small cross-sectional areas of the material are used. Small areas of very high strength but moderate stiffness material will significantly increase strength, but not stiffness.

CFRP can also be applied to enhance shear strength of reinforced concrete by wrapping fabrics or fibers around the section to be strengthened. Wrapping around sections (such as bridge or building columns) can also enhance the ductility of the section, greatly increasing the resistance to collapse under earthquake loading. Such 'seismic retrofit' is the major application in earthquake-prone areas, since it is much more economic than alternative methods.

If a column is circular (or nearly so) an increase in axial capacity is also achieved by wrapping. In this application, the confinement of the CFRP wrap enhances the compressive strength of the concrete. However, although large increases are achieved in the ultimate collapse load, the concrete will crack at only slightly enhanced load, meaning that this application is only occasionally used.

Specialist ultra-high modulus CFRP (with tensile modulus of 420 GPa or more) is one of the few practical methods of strengthening cast-iron beams. In typical use, it is bonded to the tensile flange of the section, both increasing the stiffness of the section and lowering the neutral axis, thus greatly reducing the maximum tensile stress in the cast iron.

When used as a replacement for steel, CFRP bars could be used to reinforce concrete structures, however the applications are not common.

CFRP could be used as prestressing materials due to their high strength. The advantages of CFRP over steel as a prestressing material, namely its light weight and corrosion resistance, should enable the material to be used for niche applications such as in offshore environments. However, there are practical difficulties in anchorage of carbon fiber strands and applications of this are rare.

In the United States, Prestressed Concrete Cylinder Pipes (PCCP) account for a vast majority of water transmission mains. Due to their large diameters, failures of PCCP are usually catastrophic and affect large populations. Approximately 19,000 miles of PCCP have been installed between 1940 and 2006. Corrosion in the form of hydrogen embrittlement has been blamed for the gradual deterioration of the prestressing wires in many PCCP lines. Over the past decade, CFRPs have been utilized to internally line PCCP, resulting in a fully structural strengthening system. Inside a PCCP line, the CFRP liner acts as a barrier that controls the level of strain experienced by the steel cylinder in the host pipe. The composite liner enables the steel cylinder to perform within its elastic range, to ensure the pipeline's long-term performance is maintained. CFRP liner designs are based on strain compatibility between the liner and host pipe.

CFRP is a more costly material than its counterparts in the construction industry, glass fiber-reinforced polymer (GFRP) and aramid fiber-reinforced polymer (AFRP), though CFRP is, in general, regarded as having superior properties.

Much research continues to be done on using CFRP both for retrofitting and as an alternative to steel as a reinforcing or prestressing material. Cost remains an issue and long-term durability questions still remain. Some are concerned about the brittle nature of CFRP, in contrast to the ductility of steel. Though design codes have been drawn up by institutions such as the American Concrete Institute, there remains some hesitation among the engineering community about implementing these alternative materials. In part, this is due to a lack of standardization and the proprietary nature of the fiber and resin combinations on the market, though this in itself is advantageous in that the material properties can be tailored to the desired application requirements.

Other applications

A carbon fiber and Kevlar canoe (Placid Boatworks Rapidfire at the Adirondack Canoe Classic)

Carbon fiber-reinforced polymer has found a lot of use in high-end sports equipment such as racing bicycles. For the same strength, a carbon-fiber frame weighs less than a bicycle tubing of aluminum or steel. The choice of weave can be carefully selected to maximize stiffness. The variety of shapes it can be built into has further increased stiffness and also allowed aerodynamic considerations into tube profiles. Carbon fiber-reinforced polymer frames, forks, handlebars, seatposts, and crank arms are becoming more common on medium- and higher-priced bicycles. Carbon fiber-reinforced polymer forks are used on most new racing bicycles. Other sporting goods applications include rackets, fishing rods, longboards, and rowing shells.

Much of the fuselage of the new Boeing 787 Dreamliner and Airbus A350 XWB will be composed of CFRP, making the aircraft lighter than a comparable aluminum fuselage, with the added benefit of less maintenance thanks to CFRP's superior fatigue resistance.

Due to its high ratio of strength to weight, CFRP is widely used in micro air vehicles (MAVs). In MAVSTAR Project, the CFRP structures reduce the weight of the MAV significantly. In addition, the high stiffness of the CFRP blades overcome the problem of collision between blades under strong wind.

CFRP has also found application in the construction of high-end audio components such as turntables and loudspeakers, again due to its stiffness.

It is used for parts in a variety of musical instruments, including violin bows, guitar pickguards, and a durable ebony replacement for bagpipe chanters. It is also used to create entire musical instruments such as Blackbird Guitars carbon fiber rider models, Luis and Clark carbon fiber cellos, and Mix carbon fiber mandolins.

In firearms it can substitute for metal, wood, and fiberglass in many areas of a firearm in order to reduce overall weight. However, while it is possible to make the receiver out of synthetic material such as carbon fiber, many of the internal parts are still limited to metal alloys as current reinforced plastics are unsuitable replacements.

Shoe manufacturers use carbon fiber as a shank plate in their basketball sneakers to keep the foot stable. It usually runs the length of the sneaker just above the sole and is left exposed in some areas, usually in the arch of the foot.

CFRP is used, either as standard equipment or in aftermarket parts, in high-performance radio-controlled vehicles and aircraft, i.a. for the main rotor blades of radio controlled helicopters—which should be light and stiff to perform 3D maneuvers.

Fire resistance of polymers or thermoset composites is significantly improved if a thin layer of carbon fibers is molded near the surface—dense, compact layer of carbon fibers efficiently reflects heat..

Covers of Thinkpads laptops from Lenovo/IBM and Sony use this technology.

Carbon fiber is a popular material to form the handles of high-end knives.

This material is used when manufacturing squash, tennis and badminton racquets.

Carbon-Graphite spars are used on the frames of high-end Sport kites

In 2006 Kookaburra Sport introduced cricket bats with a thin carbon fibre layer on the back which were endorsed and used in competitive matches by high-profile players including Ricky Ponting and Michael Hussey. The carbon fibre was claimed to increase the durability of the bats, however they were banned from all first-class matches by the ICC in 2007.

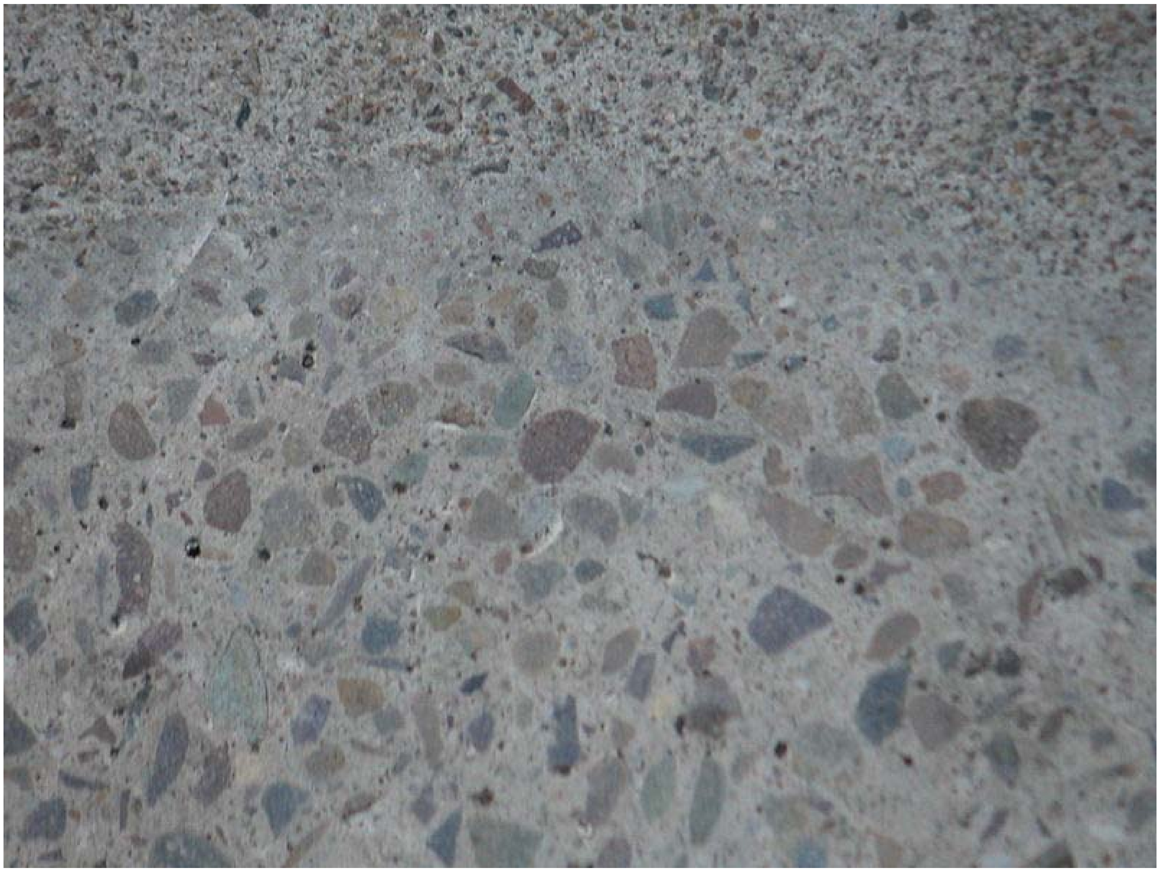
End of useful life/recycling

Carbon fiber-reinforced polymers (CFRPs) have an almost infinite service lifetime when protected from the sun, and, unlike steel alloys, have no endurance limit when exposed to cyclic loading. When it is time to decommission CFRPs, they cannot be melted down in air like many metals. When free of vinyl (PVC or polyvinyl chloride) and other halogenated polymers, CFRPs can be thermally decomposed via thermal depolymerization in an oxygen-free environment. This can be accomplished in a refinery in a one-step process. Capture and reuse of the carbon and monomers is then possible. CFRPs can also be milled or shredded at low temperature to reclaim the carbon fiber, however this process shortens the fibers dramatically. Just as with downcycled paper, the shortened fibers cause the recycled material to be weaker than the original material. There are still many industrial applications that do not need the strength of full-length carbon fiber reinforcement. For example, chopped reclaimed carbon fiber can be used in consumer electronics, such as laptops. It provides excellent reinforcement of the polymers used even if it lacks the strength-to-weight ratio of an aerospace component.

Chapter- 5

Aggregate and Cermet

Aggregate



Grinding concrete exposes aggregate stones.

Aggregate is the component of a composite material that resists compressive stress and provides bulk to the composite material. For efficient filling, aggregate should be much smaller than the finished item, but have a wide variety of sizes. For example, the particles of stone used to make concrete typically include both sand and gravel.

Comparison to fiber composites

Aggregate composites tend to be much easier to fabricate, and much more predictable in their finished properties, than *fiber composites*. This is because fiber orientation and continuity can have an overwhelming effect, but can be difficult to control and assess. Fabrication aside, aggregate materials themselves also tend to be less expensive; the most common aggregates (mentioned above) are found in nature and can often be used with only minimal processing.

Not all composite materials include aggregate in their design. This is because aggregate particles tend to have about the same dimensions in every direction (that is, an aspect ratio of about one), so that aggregate composites do not display the level of synergy that fiber composites often do. A strong aggregate held together by a weak matrix will be weak in tension, whereas fibers can be less sensitive to matrix properties, especially if they are properly oriented and run the entire length of the part (i.e., a *continuous filament*).

Most composites are filled with particles whose aspect ratio lies somewhere between oriented filaments and spherical aggregates. A good compromise is *chopped fiber*, where the performance of filament or cloth is traded off in favor of more aggregate-like processing techniques. Ellipsoid and plate-shaped aggregates are also used.

Aggregate properties

In most cases, the ideal finished piece would be 100% aggregate. A given application's most desirable quality (be it high strength, low cost, high dielectric constant, or low density) is usually most prominent in the aggregate itself; all the aggregate lacks is the ability to flow on a small scale, and form attachments between particles. The matrix is specifically chosen to serve this role, but its abilities should not be abused.

Aggregate size

Experiments and mathematical models show that more of a given volume can be filled with hard spheres if it is first filled with large spheres, then the spaces between (interstices) are filled with smaller spheres, and the new interstices filled with still smaller spheres as many times as possible. For this reason, control of *particle size distribution* can be quite important in the choice of aggregate; appropriate simulations or experiments are necessary to determine the optimal proportions of different-sized particles.

The upper limit to particle size depends on the amount of flow required before the composite sets (the gravel in paving concrete can be fairly coarse, but fine sand must be used for tile mortar), whereas the lower limit is due to the thickness of matrix material at which its properties change (clay is not included in concrete because it would "absorb" the matrix, preventing a strong bond to other aggregate particles). Particle size distribution is also the subject of much study in the fields of ceramics and powder metallurgy.

Some exceptions to this rule include:

Toughened composites

Toughness is a compromise between the (often contradictory) requirements of strength and plasticity. In many cases, the aggregate will have one of these properties, and will benefit if the matrix can add what it lacks. Perhaps the most accessible examples of this are composites with an organic matrix and ceramic aggregate, such as asphalt concrete ("tarmac") and filled plastic (i.e., Nylon mixed with powdered glass), although most metal matrix composites also benefit from this effect. In this case, the correct balance of hard and soft components is necessary or the material will become either too weak or too brittle.

Nanocomposites

Many materials properties change radically at small length scales. In the case where this change is desirable, a certain range of aggregate size is necessary to ensure good performance. This naturally sets a lower limit to the amount of matrix material used.

Unless some practical method is implemented to orient the particles in micro- or nano-composites, their small size and (usually) high strength relative to the particle-matrix bond allows any macroscopic object made from them to be treated as an aggregate composite in many respects.

While bulk synthesis of such nanoparticles as carbon nanotubes is currently too expensive for widespread use, some less extreme nanostructured materials can be synthesized by traditional methods, including electrospinning and spray pyrolysis. One important aggregate made by spray pyrolysis is glass microspheres. Often called *microballoons*, they consist of a hollow shell several tens of nanometers thick and approximately one micrometer in diameter. Casting them in a polymer matrix yields syntactic foam, with extremely high compressive strength for its low density.

Many traditional nanocomposites escape the problem of aggregate synthesis in one of two ways:

Natural aggregates: By far the most widely-used aggregates for nano-composites are naturally occurring. Usually these are ceramic materials whose crystalline structure is extremely directional, allowing it to be easily separated into flakes or fibers. The nanotechnology touted by General Motors for automotive use is in the former category: a fine-grained clay with a laminar structure suspended in a thermoplastic olefin (a class which includes many common plastics like polyethylene and polypropylene). The latter category includes fibrous asbestos composites (popular in the mid-20th century), often with matrix materials such as linoleum and Portland cement.

In-situ aggregate formation: Many micro-composites form their aggregate particles by a process of self-assembly. For example, in high impact polystyrene, two immiscible phases of polymer (including brittle polystyrene and rubbery polybutadiene) are mixed together. Special molecules (graft copolymers) include separate portions which are soluble in each phase, and so are only stable at the interface between them, in the manner of a detergent. Since the number of this type of molecule determines the interfacial area, and since spheres naturally form to minimize surface tension, synthetic chemists can control the size of polybutediene droplets in the molten mix, which harden to form rubbery aggregates in a hard matrix. Dispersion strengthening is a similar example from the field of metallurgy. In glass-ceramics, the aggregate is often chosen to have a negative coefficient of thermal expansion, and the proportion of aggregate to matrix adjusted so that the overall expansion is very near zero. Aggregate size can be reduced so that the material is transparent to infrared light.

Cermet

A **cermet** is a composite material composed of ceramic (cer) and metallic (met) materials. A cermet is ideally designed to have the optimal properties of both a ceramic, such as high temperature resistance and hardness, and those of a metal, such as the ability to undergo plastic deformation. The metal is used as a binder for an oxide, boride, or carbide. Generally, the metallic elements used are nickel, molybdenum, and cobalt. Depending on the physical structure of the material, cermets can also be metal matrix composites, but cermets are usually less than 20% metal by volume.

Cermets are used in the manufacture of resistors (especially potentiometers), capacitors, and other electronic components which may experience high temperatures.

Cermets are being used instead of tungsten carbide in saws and other brazed tools due to their superior wear and corrosion properties. Titanium nitride (TiN), Titanium carbonitride (TiCN), titanium carbide (TiC) and similar can be brazed like tungsten carbide if properly prepared however they require special handling during grinding.

More complex materials, known as Cermet 2 or Cermet II, are being utilized since they give considerably longer life in cutting tools while both brazing and grinding like tungsten carbide.

Some types of cermets are also being considered for use as spacecraft shielding as they resist the high velocity impacts of micrometeoroids and orbital debris much more effectively than more traditional spacecraft materials such as aluminum and other metals.

History

After World War II, the need to develop high temperature and high stress-resistant materials in the US became clear. During the war, German scientists developed oxide base cermets as substitutes for alloys. They saw a use for this for the high-temperature sections of new jet engines as well as high temperature turbine blades. Today ceramics are routinely implemented in the combuster part of jet engines because it provides a heat resistant chamber. Ceramic turbine blades have also been developed. These blades are lighter than steel and allow for greater acceleration of the blade assemblies.

The United States Air Force saw potential in the material technology and became one of the principal sponsors for various research programs in the US. Some of the first universities to research were Ohio State University, University of Illinois, and Rutgers University.

The word cermet was actually coined by the United States Air Force, the idea being that they are a combination of two materials, a metal and a ceramic. Basic physical properties of metals include ductility, high strength, and high thermal conductivity. Ceramics possess basic physical properties such as a high melting point, chemical stability, and especially oxidation resistance.

The first ceramic metal material developed used magnesium oxide (MgO), Beryllium oxide (BeO), and aluminum oxide (Al_2O_3) for the ceramic part. Emphasis on high stress rupture strengths was around 980C. Ohio State University was the first to develop Al_2O_3 based cermets with high stress rupture strengths around 1200C. Kennametal, a metal-working and tool company based in Latrobe, PA, developed the first titanium carbide cermet with a 2800 psi and 100 hour stress-to-rupture strength at 980C. Jet engines operate at this temperature and further research was invested on using these materials for components.

Quality control in manufacturing these ceramic metal composites was hard to standardize. Production had to be kept to small batches and within these batches, the properties varied greatly. Failure of the material was usually a result of undetected flaws usually nucleated during processing.

The existing technology in the 1950s reached a limit for jet engines where little more could be improved. Subsequently, engine manufactures were reluctant to develop ceramic metal engines.

Interest was renewed in the 1960s when silicon nitride and silicon carbide were looked at more closely. Both materials possessed better thermal shock resistance, high strength, and moderate thermal conductivity.

Applications

Ceramic-to-metal joints and seals

Cermets were first used extensively in ceramic-to-metal joint applications. Construction of vacuum tubes was one of the first critical systems, with the electronics industry employing and developing such seals. German scientists recognized that vacuum tubes with improved performance and reliability could be produced by substituting ceramics for glass. Ceramic tubes can be outgassed at higher temperatures. Because of the high-temperature seal, ceramic tubes withstand higher temperatures than glass tubes. Ceramic tubes are also mechanically stronger and less sensitive to thermal shock than glass tubes. Today, cermet vacuum tube coatings have proved to be key to solar hot water systems.

Ceramic-to-metal mechanical seals have also been used. Traditionally they have been used in fuel cells and other devices that convert chemical, nuclear, or thermionic energy to electricity. The ceramic-to-metal seal is required to isolate the electrical sections of turbine-driven generators designed to operate in corrosive liquid-metal vapors.

Bioceramics

Bioceramics play an extensive role in biomedical materials. The development of these materials and diversity of manufacturing techniques has broadened the applications that can be used in the human body. They can be in the form of thin layers on metallic implants, composites with a polymer component, or even just porous networks. These materials work well within the human body for several reasons. They are inert, and because they are resorbable and active, the materials can remain in the body unchanged. They can also dissolve and actively take part in physiological processes, for example, when hydroxylapatite, a material chemically similar to bone structure, can integrate and help bone grow into it. Common materials used for bioceramics include alumina, zirconia, calcium phosphate, glass ceramics, and pyrolytic carbons.

One important use of bioceramics is in hip replacement surgery. A hip joint essentially is a multiaxial ball and socket. The materials used for the replacement hip joints were usually metals such as titanium with the hip socket usually lined with plastic. The multiaxial ball was tough metal ball but was eventually replaced with a longer lasting ceramic ball. This reduced the roughening associated with the metal wall against the plastic lining of the artificial hip socket. The use of ceramic implants extended the life of the hip replacement parts.

Cermets are also used in dentistry as a material for fillings and prostheses.

Cermets in transportation

Ceramic parts have been used in conjunction with metal parts as friction materials for brakes and clutches.

Other applications

The United States Army and British Army have had extensive research in the development of cermets. These include the development of lightweight ceramic projectile proof armor for soldiers and also Chobham armor.

Cermets are also used in machining on cutting tools.

A cermet of depleted fissiable material (e.g. uranium, plutonium) and sodalite has been researched for its benefits in the storage of nuclear waste. Similar composites have also been researched for use as a fuel source.

Chapter- 6

Advanced Composite Materials (Science & Engineering)

Advanced composite materials (ACMs) are also known as **Advanced polymer matrix composites**. These are generally characterized or determined by unusually high strength fibres with unusually high stiffness, or modulus of elasticity characteristics, compared to other materials, while bound together by weaker matrices. These are termed advanced composite materials (ACM) in comparison to the composite materials commonly in use such as reinforced concrete, or even concrete itself. The high strength fibers are also low density while occupying a large fraction of the volume.

Advanced composites exhibit desirable physical and chemical properties that include light weight coupled with high stiffness (elasticity), and strength along the direction of the reinforcing fiber, dimensional stability, temperature and chemical resistance, flex performance, and relatively easy processing. Advanced composites are replacing metal components in many uses, particularly in the aerospace industry.

Composites are classified according to their matrix phase. There are

- polymer matrix composites (PMC's),
- ceramic matrix composites (CMC's), and
- metal matrix composites (MMC's).

Materials within these categories are often called "advanced" if they combine the properties of high (axial, longitudinal) strength values and high (axial, longitudinal) stiffness values, with low weight, corrosion resistance, and in some cases special electrical properties.

Advanced composite materials have broad, proven applications, in the aircraft, aerospace, and sports equipment sectors. Even more specifically ACMs are very attractive for aircraft and aerospace structural parts. ACMs have been developing for NASA's *Advanced Space Transportation Program*, armor protection for *Army aviation* and the *Federal Aviation Administration* of the U.S.A., and high-temperature shafting for the *Comanche helicopter*. Additionally, ACMs have a decades long history in military and government aerospace industries. However, much of the technology is new and not presented formally in secondary or undergraduate education, and the technology of advanced composites manufacture is continually evolving.

Overview and historical perspective

Manufacturing ACMs is a multibillion dollar industry in the United States. Composite products range from skateboards to components of the space shuttle. The industry can be generally divided into two basic segments, industrial composites and advanced composites. Several of the composites manufacturing processes are common to both segments. The two basic segments are described below.

Industrial composites

The industrial composites industry has been in place for over 40 years in the U.S. This large industry utilizes various resin systems including polyester, epoxy, and other specialty resins. These materials, along with a catalyst or curing agent and some type of fiber reinforcement (typically glass fibers) are used in the production of a wide spectrum of industrial components and consumer goods: boats, piping, auto bodies, and a variety of other parts and components.

Advanced composites

The Advanced polymer matrix composites industry, or Advanced composite materials industry, is characterized by the use of expensive, high-performance resin systems and high-strength, high-stiffness fiber reinforcement. The aerospace industry, including military and commercial aircraft of all types, is the major customer for advanced composites. These materials have also been adopted for use by the sporting goods suppliers who sell high-performance equipment to the golf, tennis, fishing, and archery markets.

While aerospace is the predominant market for advanced composites today, the industrial and automotive markets will increasingly see the use of advanced composites toward the year 2000. At present, both manual and automated processes are employed in making advanced-composite parts. As automated processes become more predominant, the costs of advanced composites are expected to decline to the point at which these materials will be used widely in electronic, machinery, and surface transportation equipment.

Suppliers of advanced composite materials tend to be larger companies capable of doing the research and development necessary to provide the high-performance resin systems used in this segment of the industry. End-users also tend to be large, and many are in the aircraft and aerospace businesses.

Thermosets and thermoplastics

Advanced composite systems are divided into two basic types, thermosets and thermoplastics. Thermosets are by far the predominant type in use today. Thermosets are subdivided into several resin systems including epoxies, phenolics, polyurethanes, and polyimides. Of these, epoxy systems currently dominate the advanced composite industry.

Thermosets

Thermoset resins require addition of a curing agent or hardener and impregnation onto a reinforcing material, followed by a curing step to produce a cured or finished part. Once cured, the part cannot be changed or reformed, except for finishing. Some of the more common thermosets include epoxies, polyurethanes, phenolic and amino resins, bismaleimides (BMI, polyimides), polyamides.

Of these, epoxies are the most commonly used in the industry. Epoxy resins have been in use in U.S. industry for over 40 years. Epoxy compounds are also referred to as glycidyl compounds. The epoxy molecule can also be expanded or cross-linked with other molecules to form a wide variety of resin products, each with distinct performance characteristics. These resins range from low-viscosity liquids to high-molecular weight solids. Typically they are high-viscosity liquids.

The second of the essential ingredients of an advanced composite system is the curing agent or hardener. These compounds are very important because they control the reaction rate and determine the performance characteristics of the finished part. Since these compounds act as catalysts for the reaction, they must contain active sites on their molecules. Some of the most commonly used curing agents in the advanced composite industry are the aromatic amines. Two of the most common are methylene-dianiline (MDA) and sulfonyldianiline (DDS).

Several other types of curing agents are also used in the advanced composite industry. These include aliphatic and cycloaliphatic amines, polyaminoamides, amides, and anhydrides. Again, the choice of curing agent depends on the cure and performance characteristics desired for the finished part. Polyurethanes are another group of resins used in advanced composite processes. These compounds are formed by reacting the polyol component with an isocyanate compound, typically toluene diisocyanate (TDI); methylene diisocyanate (MDI) and hexamethylene diisocyanate (HDI) are also widely used. Phenolic and amino resins are another group of PMC resins. The bismaleimides and polyamides are relative newcomers to the advanced composite industry and have not been studied to the extent of the other resins.

Thermoplastics

Thermoplastics currently represent a relatively small part of the ACM industry. They are typically supplied as nonreactive solids (no chemical reaction occurs during processing) and require only heat and pressure to form the finished part. Unlike the thermosets, the thermoplastics can usually be reheated and reformed into another shape, if desired.

Fiber reinforcments

Fiber reinforcement materials are added to the resin system to provide strength to the finished part. The selection of reinforcement material is based on the properties desired in the finished product. These materials do not react with the resin but are an integral part of the advanced composite system.

The three basic types of fiber reinforcement materials in use in the advanced composite industry are

- carbon/graphite
- aramid
- glass fibers

Fibers used in advanced composite manufacture come in various forms, including yarns, rovings, chopped strands, and woven fabric mats. Each of these has its own special application. When prepreg materials are used in parts manufacture, woven fabric or mats are required. In processes such as filament wet winding or pultrusion, yarns and rovings are used.

Prepreg

Resin-impregnated cloth, mat, or filaments in flat form that can be stored for later use. The resin is often partially cured to a tack-free state called "B-staging." Catalysts, inhibitors, flame retardants, and other additives may be included to obtain specific end-use properties and improve processing, storage, and handling characteristics.

Limitations

Despite their strength and low weight, composites have not been a miracle solution for aircraft structures. Composites are hard to inspect for flaws. Some of them absorb moisture. Most importantly, they can be expensive, primarily because they are labor intensive and often require complex and expensive fabrication machines. Aluminum, by contrast, is easy to manufacture and repair. Anyone who has ever gotten into a minor car accident has learned that dented metal can be hammered back into shape, but a crunched fiberglass bumper has to be completely replaced. The same is true for many composite materials used in aviation.

Aluminum is a very tolerant material and can take a great deal of punishment before it fails. It can be dented or punctured and still hold together. Composites are not like this. If they are damaged, they require immediate repair, which is difficult and expensive. An airplane made entirely from aluminum can be repaired almost anywhere. This is not the case for composite materials, particularly as they use different and more exotic materials. Because of this, composites will probably always be used more in military aircraft, which are constantly being maintained, than in commercial aircraft, which have to require less maintenance.

Aluminum still remains a remarkably useful material for aircraft structures and metallurgists have worked hard to develop better aluminum alloys (a mixture of aluminum and other materials). In particular, aluminum-lithium is the most successful of these alloys. It is approximately ten percent lighter than standard aluminum. Beginning in the later 1990s it was used for the Space Shuttle's large External Tank in order to reduce weight and enable the shuttle to carry more payload. Its adoption by commercial aircraft manufacturers has been slower, however, due to the expense of lithium and the greater difficulty of using aluminum-lithium (in particular, it requires much care during welding). But it is likely that aluminum-lithium will eventually become a widely used material for both commercial and military aircraft.

Metal matrix composite

A **metal matrix composite** (**MMC**) is composite material with at least two constituent parts, one being a metal. The other material may be a different metal or another material, such as a ceramic or organic compound. When at least three materials are present, it is called a **hybrid composite**. An MMC is complementary to a cermet.

Composition

MMCs are made by dispersing a reinforcing material into a metal matrix. The reinforcement surface can be coated to prevent a chemical reaction with the matrix. For example, carbon fibers are commonly used in aluminium matrix to synthesize composites showing low density and high strength. However, carbon reacts with aluminium to generate a brittle and water-soluble compound Al_4C_3 on the surface of the fiber. To prevent this reaction, the carbon fibers are coated with nickel or titanium boride.

Matrix

The matrix is the monolithic material into which the reinforcement is embedded, and is completely continuous. This means that there is a path through the matrix to any point in the material, unlike two materials sandwiched together. In structural applications, the matrix is usually a lighter metal such as aluminium, magnesium, or titanium, and provides a compliant support for the reinforcement. In high temperature applications, cobalt and cobalt-nickel alloy matrices are common.

Reinforcement

The reinforcement material is embedded into the matrix. The reinforcement does not always serve a purely structural task (reinforcing the compound), but is also used to change physical properties such as wear resistance, friction coefficient, or thermal conductivity. The reinforcement can be either continuous, or discontinuous. Discontinuous MMCs can be isotropic, and can be worked with standard metalworking techniques, such as extrusion, forging or rolling. In addition, they may be machined using conventional techniques, but commonly would need the use of polycrystaline diamond tooling (PCD).

Continuous reinforcement uses monofilament wires or fibers such as carbon fiber or silicon carbide. Because the fibers are embedded into the matrix in a certain direction, the result is an anisotropic structure in which the alignment of the material affects its strength. One of the first MMCs used boron filament as reinforcement. Discontinuous reinforcement uses "whiskers", short fibers, or particles. The most common reinforcing materials in this category are alumina and silicon carbide.

Manufacturing and forming methods

MMC manufacturing can be broken into three types: solid, liquid, and vapor.

Solid state methods

- Powder blending and consolidation (powder metallurgy): Powdered metal and discontinuous reinforcement are mixed and then bonded through a process of compaction, degassing, and thermo-mechanical treatment (possibly via hot isostatic pressing (HIP) or extrusion).
- Foil diffusion bonding: Layers of metal foil are sandwiched with long fibers, and then pressed through to form a matrix.

Liquid state methods

- Electroplating / Electroforming: A solution containing metal ions loaded with reinforcing particles is co-deposited forming a composite material.
- Stir casting: Discontinuous reinforcement is stirred into molten metal, which is allowed to solidify.
- Squeeze casting: Molten metal is injected into a form with fibers preplaced inside it.
- Spray deposition: Molten metal is sprayed onto a continuous fiber substrate.
- Reactive processing: A chemical reaction occurs, with one of the reactants forming the matrix and the other the reinforcement.

Vapor deposition

- Physical vapor deposition: The fiber is passed through a thick cloud of vaporized metal, coating it.

In situ fabrication technique

- Controlled unidirectional solidification of a eutectic alloy can result in a two-phase microstructure with one of the phases, present in lamellar or fiber form, distributed in the matrix.

Applications

- Carbide drills are often made from a tough cobalt matrix with hard tungsten carbide particles inside.
- Some tank armors may be made from metal matrix composites, probably steel reinforced with boron nitride. Boron nitride is a good reinforcement for steel because it is very stiff and it does not dissolve in molten steel.
- Some automotive disc brakes use MMCs. Early Lotus Elise models used aluminium MMC rotors, but they have less than optimal heat properties and Lotus has since switched back to cast-iron. Modern high-performance sport cars, such as those built by Porsche, use rotors made of carbon fiber within a silicon carbide matrix because of its high specific heat and thermal conductivity. 3M sells a preformed aluminium matrix insert for strengthening cast aluminum disc brake calipers, allowing them to weigh as much as 50% less while increasing stiffness. 3M has also used alumina preforms for AMC pushrods.
- Ford offers a Metal Matrix Composite (MMC) driveshaft upgrade. The MMC driveshaft is made of an aluminum matrix reinforced with boron carbide, allowing the critical speed of the driveshaft to be raised by reducing inertia. The MMC driveshaft has become a common modification for racers, allowing the top speed to be increased far beyond the safe operating speeds of a standard aluminum driveshaft.
- Honda has used aluminium metal matrix composite cylinder liners in some of their engines, including the B21A1, H22A and H23A, F20C and F22C, and the C32B used in the NSX.
- Toyota has since used metal matrix composites in the Yamaha-designed 2ZZ-GE engine which is used in the later Lotus Lotus Elise S2 versions as well as Toyota car models, including the eponymous Toyota Matrix. Porsche also uses MMCs to reinforce the engine's cylinder sleeves in the Boxster and 911.
- The F-16 Fighting Falcon uses monofilament silicon carbide fibers in a titanium matrix for a structural component of the jet's landing gear.
- Specialized Bicycles has used aluminum MMC compounds for its top of the range bicycle frames for several years. Griffen Bicycles also makes boron carbide-aluminum MMC bike frames, and Univega briefly did so as well.
- Some equipment in particle accelerators such as Radio Frequency Quadrupoles (RFQs) or electron targets use copper MMC compounds such as Glidcop to retain the material properties of copper at high temperatures and radiation levels.
- Copper-silver alloy matrix containing 55 vol.% diamond particles, known as Dymalloy, is used as a substrate for high-power and high density multi-chip modules in electronics for its very high thermal conductivity.

MMCs are nearly always more expensive than the more conventional materials they are replacing. As a result, they are found where improved properties and performance can justify the added cost. Today these applications are found most often in aircraft components, space systems and high-end or "boutique" sports equipment. The scope of applications will certainly increase as manufacturing costs are reduced.

In comparison with conventional polymer matrix composites, MMCs are resistant to fire, can operate in wider range of temperatures, do not absorb moisture, have better electrical and thermal conductivity, are resistant to radiation damage, and do not display outgassing. On the other hand, MMCs tend to be more expensive, the fiber-reinforced materials may be difficult to fabricate, and the available experience in use is limited.

Chapter- 7

Glass (fiber)

Bundle of fiberglass

Fiberglass, (also called **fibreglass** and **glass fibre**), is a material consisting of numerous extremely fine fibers of glass.

Glassmakers throughout history have experimented with glass fibers, but mass manufacture of fiberglass was only made possible with the invention of finer machine tooling. In 1893, Edward Drummond Libbey exhibited a dress at the World's Columbian Exposition incorporating glass fibers with the diameter and texture of silk fibers. This was first worn by the popular stage actress of the time Georgia Cayvan.

Glass wool, which is commonly known as "fiberglass" today, however, was invented in 1938 by Russell Games Slayter of Owens-Corning as a material to be used as insulation. It is marketed under the trade name **Fiberglas,** which has become a genericized trademark.

Fiberglass is commonly used as an insulating material. It is also used as a reinforcing agent for many polymer products; the resulting composite material, properly known as fiber-reinforced polymer (FRP) or glass-reinforced plastic (GRP), is also called "fiberglass" in popular usage.

A somewhat similar, but more expensive technology used for applications requiring very high strength and low weight is the use of carbon fiber.

Fiber formation

Glass fiber is formed when thin strands of silica-based or other formulation glass is extruded into many fibers with small diameters suitable for textile processing. The technique of heating and drawing glass into fine fibers has been known for millennia; however, the use of these fibers for textile applications is more recent. Until this time all fiberglass had been manufactured as staple (a term used to describe naturally formed clusters or locks of wool fibres). The first commercial production of fiberglass was in 1936. In 1938 Owens-Illinois Glass Company and Corning Glass Works joined to form the Owens-Corning Fiberglas Corporation. When the two companies joined to produce and promote fiberglass, they introduced continuous filament glass fibers. Owens-Corning is still the major fiberglass producer in the market today.

The types of fiberglass most commonly used are mainly E-glass (alumino-borosilicate glass with less than 1 wt% alkali oxides, mainly used for glass-reinforced plastics), but also A-glass (alkali-lime glass with little or no boron oxide), E-CR-glass (alumino-lime silicate with less than 1 wt% alkali oxides, has high acid resistance), C-glass (alkali-lime glass with high boron oxide content, used for example for glass staple fibers), D-glass (borosilicate glass with high dielectric constant), R-glass (alumino silicate glass without MgO and CaO with high mechanical requirements), and S-glass (alumino silicate glass without CaO but with high MgO content with high tensile strength).

Chemistry

Although pure silica is a perfectly viable glass and glass fiber, it must be worked with at very high temperatures, which is a drawback unless its specific chemical properties are needed. It is usual to introduce impurities into the glass in the form of other materials to lower its working temperature. These materials also impart various other properties to the glass that may be beneficial in different applications. The first type of glass used for fiber was soda lime glass or A glass. It was not very resistant to alkali. A new type, E-glass, was formed; this is an alumino-borosilicate glass that is alkali free (<2%). This was the first glass formulation used for continuous filament formation. E-glass still makes up most of the fiberglass production in the world. Its particular components may differ slightly in percentage, but must fall within a specific range. The letter E is used because it was originally for electrical applications. S-glass is a high-strength formulation for use when tensile strength is the most important property. C-glass was developed to resist attack from chemicals, mostly acids that destroy E-glass. T-glass is a North American variant of C-glass. A-glass is an industry term for cullet glass, often bottles, made into fiber. AR-glass is alkali-resistant glass. Most glass fibers have limited solubility in water but are very dependent on pH. Chloride ions will also attack and dissolve E-glass surfaces.

Since E-glass does not really melt, but soften, the softening point is defined as "the temperature at which a 0.55–0.77 mm diameter fiber 235 mm long, elongates under its own weight at 1 mm/min when suspended vertically and heated at the rate of 5°C per minute". The strain point is reached when the glass has a viscosity of $10^{14.5}$ poise. The annealing point, which is the temperature where the internal stresses are reduced to an acceptable commercial limit in 15 minutes, is marked by a viscosity of 10^{13} poise.

Properties

Thermal

Glass fibers are useful because of their high ratio of surface area to weight. However, the increased surface area makes them much more susceptible to chemical attack. By trapping air within them, blocks of glass fiber make good thermal insulation, with a thermal conductivity of the order of 0.05 W/(m·K).

Tensile

Fiber type	Tensile strength (MPa)	Density (g/cm^3)
E-Glass	3,450	2.57
S-Glass	4,710	2.48

The strength of glass is usually tested and reported for "virgin" or pristine fibers—those that have just been manufactured. The freshest, thinnest fibers are the strongest because the thinner fibers are more ductile. The more the surface is scratched, the less the resulting tenacity. Because glass has an amorphous structure, its properties are the same along the fiber and across the fiber. Humidity is an important factor in the tensile strength. Moisture is easily adsorbed, and can worsen microscopic cracks and surface defects, and lessen tenacity.

In contrast to carbon fiber, glass can undergo more elongation before it breaks. There is a correlation between bending diameter of the filament and the filament diameter. The viscosity of the molten glass is very important for manufacturing success. During drawing (pulling of the glass to reduce fiber circumference), the viscosity should be relatively low. If it is too high, the fiber will break during drawing. However, if it is too low, the glass will form droplets rather than drawing out into fiber.

Safety

Fiberglass has increased in popularity since the discovery that asbestos causes cancer and its subsequent removal from most products. However, the safety of fiberglass is also being called into question, as research shows that the composition of this material (asbestos and fiberglass are both silicate fibers) causes similar toxicity as asbestos.

1970s studies on rats found that fibrous glass of less than 3 micrometers in diameter and greater than 20 micrometers in length is a "potent carcinogen". Likewise, the International Agency for Research on Cancer found it "may reasonably be anticipated to be a carcinogen" in 1990. The American Conference of Governmental Industrial Hygienists, on the other hand, says that there is insufficient evidence, and that fiberglass is in group A4: "Not classifiable as a human carcinogen".

The North American Insulation Manufacturers Association (NAIMA) claims that fiberglass is fundamentally different from asbestos, since it is man-made instead of naturally-occurring. They claim that fiberglass "dissolves in the lungs", while asbestos remains in the body for life. Although both fiberglass and asbestos are made from silica filaments, NAIMA claims that asbestos is more dangerous because of its crystalline structure, which causes it to cleave into smaller, more dangerous pieces, citing the U.S. Department of Health and Human Services:

Synthetic vitreous fibers [fiber glass] differ from asbestos in two ways that may provide at least partial explanations for their lower toxicity. Because most synthetic vitreous fibers are not crystalline like asbestos, they do not split longitudinally to form thinner fibers. They also generally have markedly less biopersistence in biological tissues than asbestos fibers because they can undergo dissolution and transverse breakage.

A 1998 rat study found that the biopersistence of synthetic fibers after one year was 0.04–10%, but 27% for amosite asbestos. Fibers that persisted longer were found to be more carcinogenic.

Glass-reinforced plastic

Glass-reinforced plastic (GRP) is a composite material or fiber-reinforced plastic made of a plastic reinforced by fine glass fibers. Like graphite-reinforced plastic, the composite material is commonly referred to by the name of its reinforcing fibers (fiberglass). Thermosetting plastics are normally used for GRP production—most often unsaturated polyester (using 2-butanone peroxide aka MEK peroxide as a catalyst), but vinylester or epoxy are also used. Traditionally, styrene monomer was used as a reactive diluent in the resin formulation giving the resin a characteristic odor. More recently alternatives have been developed. The glass can be in the form of a chopped strand mat (CSM) or a woven fabric.

As with many other composite materials (such as reinforced concrete), the two materials act together, each overcoming the deficits of the other. Whereas the plastic resins are strong in compressive loading and relatively weak in tensile strength, the glass fibers are very strong in tension but have no strength against compression. By combining the two materials, GRP becomes a material that resists both compressive and tensile forces well. The two materials may be used uniformly or the glass may be specifically placed in those portions of the structure that will experience tensile loads.

Uses

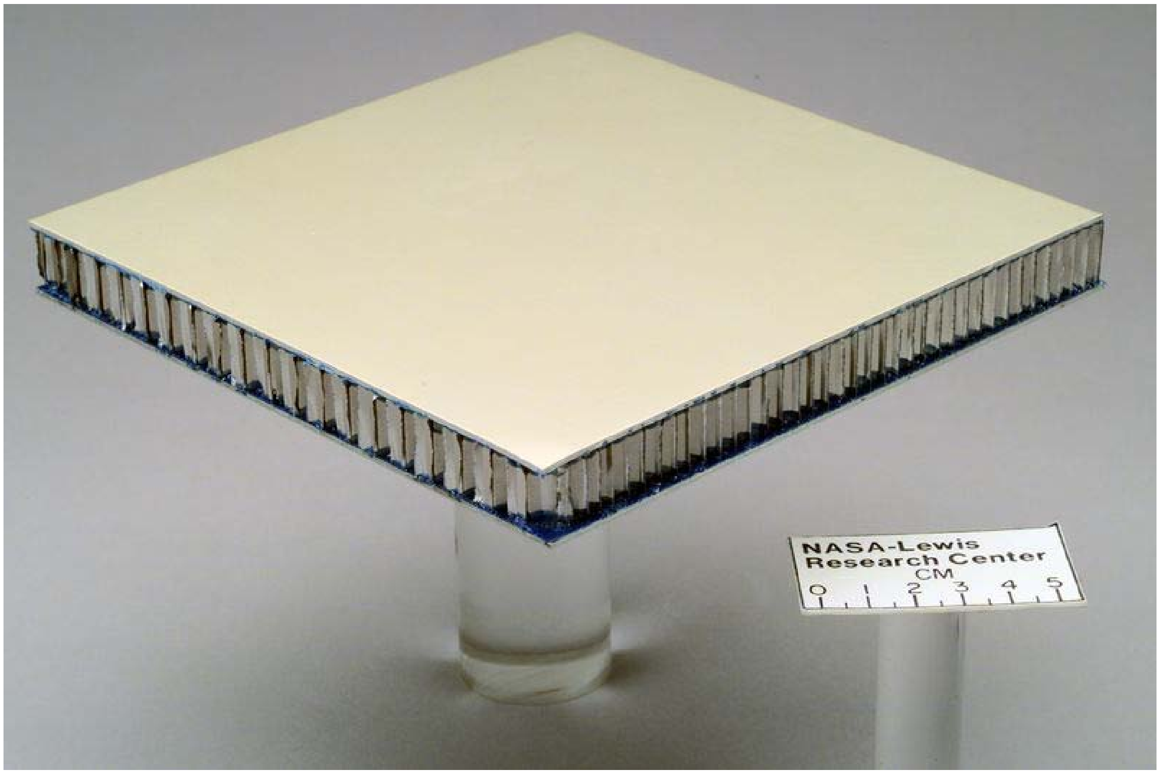
Uses for regular fiberglass include mats, thermal insulation, electrical insulation, sound insulation, reinforcement of various materials, tent poles, sound absorption, heat- and corrosion-resistant fabrics, high-strength fabrics, pole vault poles, arrows, bows and crossbows, translucent roofing panels, automobile bodies, hockey sticks, surfboards, boat hulls, and paper honeycomb. It has been used for medical purposes in casts. Fiberglass is extensively used for making FRP tanks and vessels. Fiberglass is also used in the design of Irish stepdance shoes.

Role of recycling in fiberglass manufacturing

Manufacturers of fiberglass insulation can use recycled glass. Owens Corning's fiberglass has 40% recycled glass. A recycling program begun in 2009 in Kansas City, Kansas, will ship crushed recycled glass, called cullet, to the Owens Corning plant that will use it as raw material for fiberglass making.

Chapter- 8

Sandwich Theory



Composite sandwich structure panel used for testing at NASA

Sandwich theory describes the behaviour of a beam, plate, or shell which consists of three layers - two facesheets and one core. The most commonly used sandwich theory is linear and is an extension of first order beam theory. Linear sandwich theory is of importance for the design and analysis of sandwich panels, which are of use in building construction, vehicle construction, airplane construction and refrigeration engineering.

Some advantages of sandwich construction are:

- Sandwich cross sections are composite. They usually consist of a low to moderate stiffness core which is connected with two stiff exterior face-sheets. The composite has a considerably higher shear stiffness to weight ratio than an

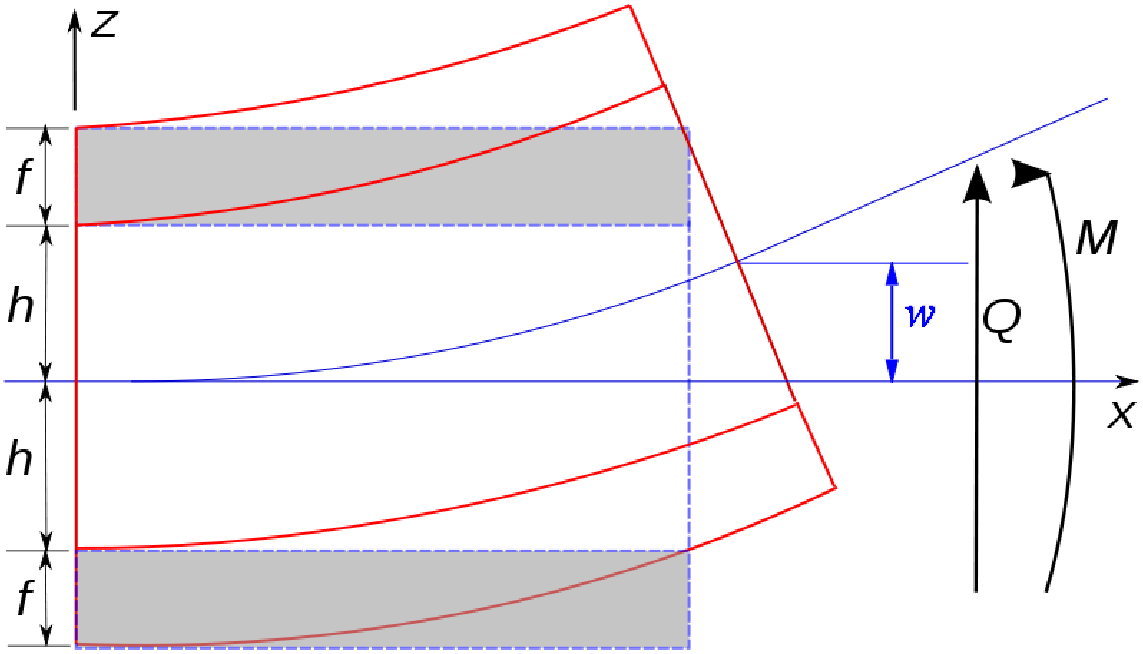
equivalent beam made of only the core material or the face-sheet material. The composite also has a high tensile strength to weight ratio.
- The high stiffness of the face-sheet leads to a high bending stiffness to weight ratio for the composite.

The behavior of a beam with sandwich cross-section under a load differs from a beam with a constant elastic cross section as can be observed in the adjacent figure. If the radius of curvature during bending is small compared to the thickness of a sandwich beam and the strains in the component materials are small, the deformation of a sandwich composite beam can be separated into two parts

- deformations due to bending moments or bending deformation, and
- deformations due to transverse forces, also called shear deformation.

Sandwich beam, plate, and shell theories usually assume that the reference stress state is one of zero stress. However, during curing, differences of temperature between the face-sheets persist because of the thermal separation by the core material. These temperature differences, coupled with different linear expansions of the face-sheets, can lead to a bending of the sandwich beam in the direction of the warmer face-sheet. If the bending is constrained during the manufacturing process, residual stresses can develop in the components of a sandwich composite. The superposition of a reference stress state on the solutions provided by sandwich theory is possible when the problem is linear. However, when large elastic deformations and rotations are expected, the initial stress state has to be incorporated directly into the sandwich theory.

Engineering sandwich beam theory



Bending of a sandwich beam without extra deformation due to core shear

In the engineering theory of sandwich beams, the axial strain is assumed to vary linearly over the cross-section of the beam as in Euler-Bernoulli theory, i.e.,

$$\varepsilon_{xx}(x,z) = -z~\frac{\mathrm{d}^2w}{\mathrm{d}x^2}$$

Therefore the axial stress in the sandwich beam is given by

$$\sigma_{xx}(x,z) = -z~E(z)~\frac{\mathrm{d}^2w}{\mathrm{d}x^2}$$

where $E(z)$ is the Young's modulus which is a function of the location along the thickness of the beam. The bending moment in the beam is then given by

$$M_x(x) = \int z~\sigma_{xx}~\mathrm{d}z = -\left(\int z^2E(z)~\mathrm{d}z\right)~\frac{\mathrm{d}^2w}{\mathrm{d}x^2} = -D~\frac{\mathrm{d}^2w}{\mathrm{d}x^2}$$

The quantity D is called the **flexural stiffness** of the sandwich beam. The shear force Q_x is defined as

$$Q_x = \frac{\mathrm{d}M_x}{\mathrm{d}x}~.$$

Using these relations, we can show that the stresses in a sandwich beam with a core of thickness $2h$ and modulus E^c and two facesheets each of thickness f and modulus E^f, are given by

$$\sigma_{xx}^{\mathrm{f}} = \frac{zE^{\mathrm{f}}M_x}{D} ~; \qquad \sigma_{xx}^{\mathrm{c}} = \frac{zE^{\mathrm{c}}M_x}{D}$$

$$\tau_{xz}^{\mathrm{f}} = \frac{Q_xE^{\mathrm{f}}}{2D}\left[(h+f)^2 - z^2\right] ~; \qquad \tau_{xz}^{\mathrm{c}} = \frac{Q_x}{2D}\left[E^{\mathrm{c}}\left(h^2 - z^2\right) + E^{\mathrm{f}}f(f+2h)\right]$$

For a sandwich beam with identical facesheets the value of D is

$$\begin{aligned} D &= E^f \int_{-h-f}^{-h} z^2~\mathrm{d}z + E^c \int_{-h}^{h} z^2~\mathrm{d}z + E^f \int_{h}^{h+f} z^2~\mathrm{d}z \\ &= \frac{2}{3}E^f f^3 + \frac{2}{3}E^c h^3 + 2E^f fh(f+h) ~. \end{aligned}$$

If $E^f \gg E^c$, then D can be approximated as

$$D \approx \frac{2}{3}E^f f^3 + 2E^f fh(f+h) = fE^f\left(\frac{2}{3}f^2 + h(f+h)\right)$$

and the stresses in the sandwich beam can be approximated as

$$\sigma_{xx}^{\mathrm{f}} \approx \frac{zM_x}{\frac{2}{3}f^3 + 2fh(f+h)} ~; \qquad \sigma_{xx}^{\mathrm{c}} \approx 0$$

$$\tau_{xz}^{\mathrm{f}} \approx \frac{Q_x}{\frac{4}{3}f^3 + 4fh(f+h)}\left[(h+f)^2 - z^2\right] ~; \qquad \tau_{xz}^{\mathrm{c}} \approx \frac{Q_x(f+2h)}{\frac{2}{3}f^2 + h(f+h)}$$

If, in addition, $f \ll 2h$, then

$$D \approx 2E^f fh(f+h)$$

and the approximate stresses in the beam are

$$\sigma_{xx}^{\mathrm{f}} \approx \frac{zM_x}{2fh(f+h)} ~; \qquad \sigma_{xx}^{\mathrm{c}} \approx 0$$

$$\tau_{xz}^{\mathrm{f}} \approx \frac{Q_x}{4fh(f+h)}\left[(h+f)^2 - z^2\right] ~; \qquad \tau_{xz}^{\mathrm{c}} \approx \frac{Q_x(f+2h)}{4h(f+h)} \approx \frac{Q_x}{2h}$$

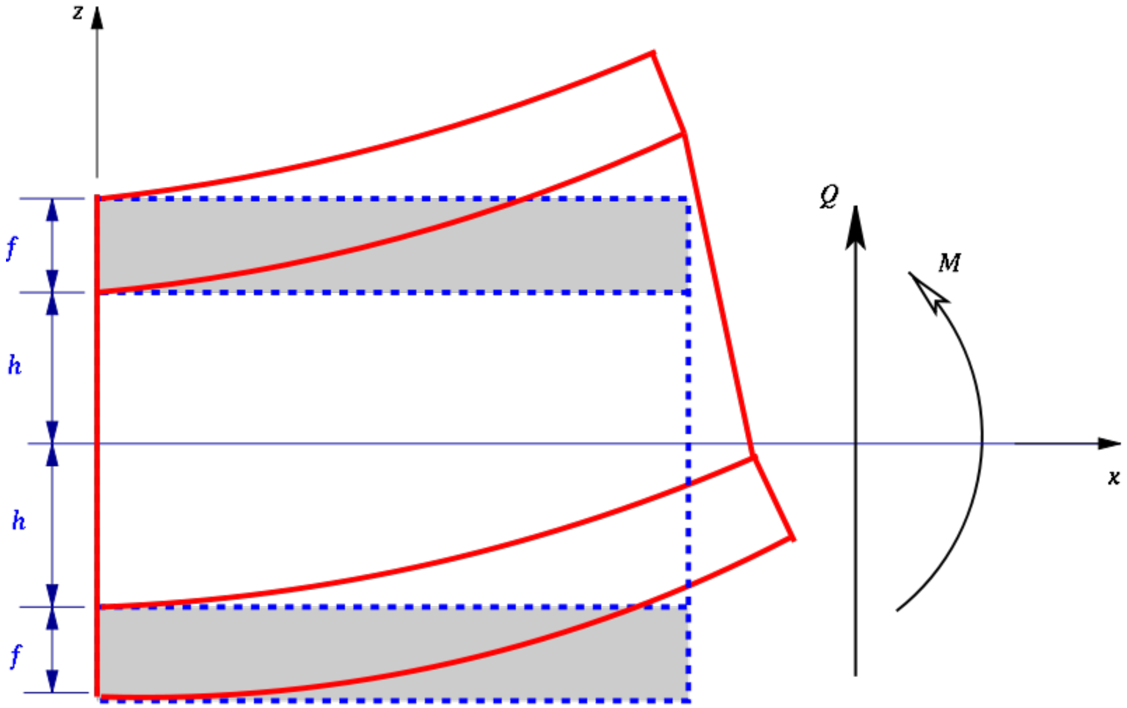
If we assume that the facesheets are thin enough that the stresses may be assumed to be constant through the thickness, we have the approximation

$$\sigma_{xx}^{\rm f} \approx \pm \frac{M_x}{2fh} ~; \qquad \sigma_{xx}^{\rm c} \approx 0$$
$$\tau_{xz}^{\rm f} \approx 0 ~; \qquad \tau_{xz}^{\rm c} \approx \frac{Q_x}{2h}$$

Hence the problem can be split into two parts, one involving only core shear and the other involving only bending stresses in the facesheets.

Linear sandwich theory

Bending of a sandwich beam with thin facesheets



Bending of a sandwich beam after incorporating shear of the core into the deformation

The main assumptions of linear sandwich theories of beams with thin facesheets are:

- the transverse normal stiffness of the core is infinite, i.e., the core thickness in the z-direction does not change during bending
- the in-plane normal stiffness of the core is small compared to that of the facesheets, i.e., the core does not lengthen or compress in the x-direction

- the facesheets behave according to the Euler-Bernoulli assumptions, i.e., there is no xz-shear in the facesheets and the z-direction thickness of the facesheets does not change

However, the xz shear-stresses in the core are not neglected.

Constitutive assumptions

The constitutive relations relations for two-dimensional orthotropic linear elastic materials are

$$\begin{bmatrix}\sigma_{xx}\\ \sigma_{zz}\\ \sigma_{zx}\end{bmatrix} = \begin{bmatrix}C_{11} & C_{13} & 0\\ C_{13} & C_{33} & 0\\ 0 & 0 & C_{55}\end{bmatrix}\begin{bmatrix}\varepsilon_{xx}\\ \varepsilon_{zz}\\ \varepsilon_{zx}\end{bmatrix}$$

The assumptions of sandwich theory lead to the simplified relations

$$\sigma_{xx}^{\text{face}} = C_{11}^{\text{face}}\,\varepsilon_{xx}^{\text{face}}~;~~\sigma_{zx}^{\text{core}} = C_{55}^{\text{core}}\,\varepsilon_{zx}^{\text{core}}~;~~\sigma_{zz}^{\text{face}} = \sigma_{xz}^{\text{face}} = 0~;~~\sigma_{zz}^{\text{core}} = \sigma_{xx}^{\text{core}} = 0$$

and

$$\varepsilon_{zz}^{\text{face}} = \varepsilon_{xz}^{\text{face}} = 0~;~~\varepsilon_{zz}^{\text{core}} = \varepsilon_{xx}^{\text{core}} = 0$$

The equilibrium equations in two dimensions are

$$\frac{\partial\sigma_{xx}}{\partial x} + \frac{\partial\sigma_{zx}}{\partial z} = 0~;~~\frac{\partial\sigma_{zx}}{\partial x} + \frac{\partial\sigma_{zz}}{\partial z} = 0$$

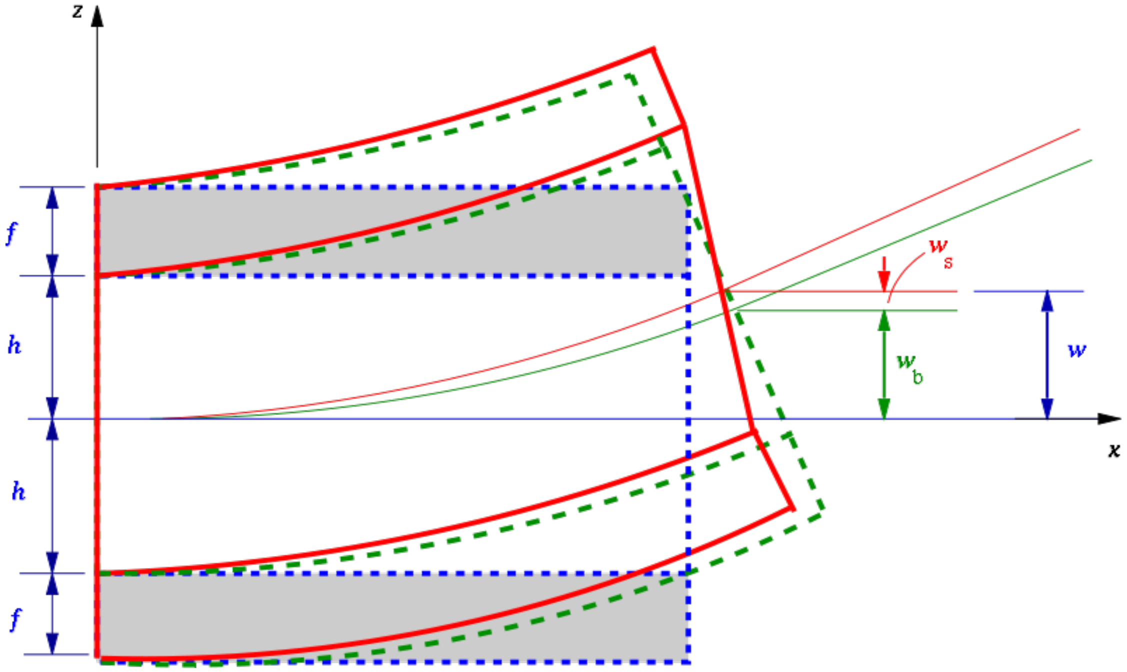
The assumptions for a sandwich beam and the equilibrium equation imply that

$$\sigma_{xx}^{\text{face}} \equiv \sigma_{xx}^{\text{face}}(z)~;~~\sigma_{zx}^{\text{core}} = \text{constant}$$

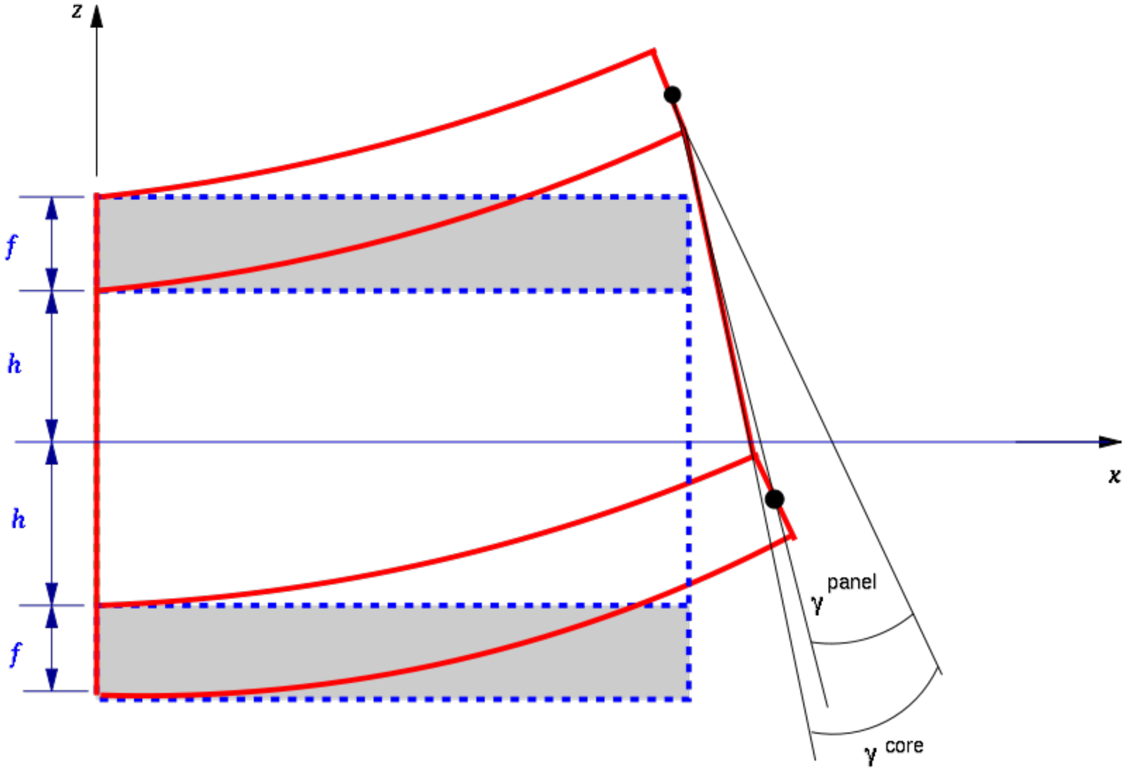
Therefore, for homogeneous facesheets and core, the strains also have the form

$$\varepsilon_{xx}^{\text{face}} \equiv \varepsilon_{xx}^{\text{face}}(z)~;~~\varepsilon_{zx}^{\text{core}} = \text{constant}$$

Kinematics



Bending of a sandwich beam. The total deflection is the sum of a bending part w_b and a shear part w_s



Shear strains during the bending of a sandwich beam

Let the sandwich beam be subjected to a bending moment *M* and a shear force *Q*. Let the total deflection of the beam due to these loads be *w*. The adjacent figure shows that, for small displacements, the total deflection of the mid-surface of the beam can be expressed as the sum of two deflections, a pure bending deflection w_b and a pure shear deflection w_s, i.e.,

$$w(x) = w_b(x) + w_s(x)$$

From the geometry of the deformation we observe that the engineering shear strain (γ) in the core is related the effective shear strain in the composite by the relation

$$\gamma_{zx}^{\text{core}} = \tfrac{2h+f}{2h}\ \gamma_{zx}^{\text{beam}}$$

Note the shear strain in the core is larger than the effective shear strain in the composite and that small deformations ($\tan\gamma = \gamma$) are assumed in deriving the above relation. The effective shear strain in the beam is related to the shear displacement by the relation

$$\gamma_{zx}^{\text{beam}} = \frac{\mathrm{d}w_s}{\mathrm{d}x}$$

The facesheets are assumed to deform in accordance with the assumptions of Euler-Bernoulli beam theory. The total deflection of the facesheets is assumed to be the superposition of the deflections due to bending and that due to core shear. The *x*-direction displacements of the facesheets due to bending are given by

$$u_b^{\text{face}}(x,z) = -z\ \frac{\mathrm{d}w_b}{\mathrm{d}x}$$

The displacement of the top facesheet due to shear in the core is

$$u_s^{\text{topface}}(x,z) = -\left(z - h - \tfrac{f}{2}\right)\ \frac{\mathrm{d}w_s}{\mathrm{d}x}$$

and that of the bottom facesheet is

$$u_s^{\text{botface}}(x,z) = -\left(z + h + \tfrac{f}{2}\right)\ \frac{\mathrm{d}w_s}{\mathrm{d}x}$$

The normal strains in the two facesheets are given by

$$\varepsilon_{xx} = \frac{\partial u_b}{\partial x} + \frac{\partial u_s}{\partial x}$$

Therefore

$$\varepsilon_{xx}^{\text{topface}} = -z\ \frac{\mathrm{d}^2 w_b}{\mathrm{d}x^2} - \left(z - h - \tfrac{f}{2}\right)\ \frac{\mathrm{d}^2 w_s}{\mathrm{d}x^2};\ \varepsilon_{xx}^{\text{botface}} = -z\ \frac{\mathrm{d}^2 w_b}{\mathrm{d}x^2} - \left(z + h + \tfrac{f}{2}\right)\ \frac{\mathrm{d}^2 w_s}{\mathrm{d}x^2}$$

Stress-displacement relations

The shear stress in the core is given by

$$\sigma_{zx}^{\text{core}} = C_{55}^{\text{core}}\ \varepsilon_{zx}^{\text{core}} = \frac{C_{55}^{\text{core}}}{2}\ \gamma_{zx}^{\text{core}} = \tfrac{2h+f}{4h}\ C_{55}^{\text{core}}\ \gamma_{zx}^{\text{beam}}$$

or,

$$\sigma_{zx}^{\text{core}} = \tfrac{2h+f}{4h}\ C_{55}^{\text{core}}\ \frac{\mathrm{d}w_s}{\mathrm{d}x}$$

The normal stresses in the facesheets are given by

$$\sigma_{xx}^{\text{face}} = C_{11}^{\text{face}}\ \varepsilon_{xx}^{\text{face}}$$

Hence,

$$\begin{aligned}
\sigma_{xx}^{\text{topface}} &= -z\ C_{11}^{\text{face}}\ \frac{\mathrm{d}^2 w_b}{\mathrm{d}x^2} - \left(z - h - \tfrac{f}{2}\right)\ C_{11}^{\text{face}}\ \frac{\mathrm{d}^2 w_s}{\mathrm{d}x^2} &&= -\ z\ C_{11}^{\text{face}}\ \frac{\mathrm{d}^2 w}{\mathrm{d}x^2} + \left(\tfrac{2h+f}{2}\right)\ C_{11}^{\text{face}}\ \frac{\mathrm{d}^2 w_s}{\mathrm{d}x^2} \\
\sigma_{xx}^{\text{botface}} &= -z\ C_{11}^{\text{face}}\ \frac{\mathrm{d}^2 w_b}{\mathrm{d}x^2} - \left(z + h + \tfrac{f}{2}\right)\ C_{11}^{\text{face}}\ \frac{\mathrm{d}^2 w_s}{\mathrm{d}x^2} &&= -\ z\ C_{11}^{\text{face}}\ \frac{\mathrm{d}^2 w}{\mathrm{d}x^2} - \left(\tfrac{2h+f}{2}\right)\ C_{11}^{\text{face}}\ \frac{\mathrm{d}^2 w_s}{\mathrm{d}x^2}
\end{aligned}$$

Resultant forces and moments

The resultant normal force in a facesheet is defined as

$$N_{xx}^{\text{face}} := \int_{-f/2}^{f/2} \sigma_{xx}^{\text{face}}\ \mathrm{d}z_f$$

and the resultant moments are defined as

$$M_{xx}^{\text{face}} := \int_{-f/2}^{f/2} z_f\ \sigma_{xx}^{\text{face}}\ \mathrm{d}z_f$$

where

$$z_f^{\text{topface}} := z - h - \tfrac{f}{2}\ ;\quad z_f^{\text{botface}} := z + h + \tfrac{f}{2}$$

Using the expressions for the normal stress in the two facesheets gives

$$N_{xx}^{\rm topface} = -f\left(h + \tfrac{f}{2}\right)\ C_{11}^{\rm face}\ \frac{{\rm d}^2 w_b}{{\rm d}x^2} = -N_{xx}^{\rm botface}$$

$$M_{xx}^{\rm topface} = -\frac{f^3\ C_{11}^{\rm face}}{12}\left(\frac{{\rm d}^2 w_b}{{\rm d}x^2} + \frac{{\rm d}^2 w_s}{{\rm d}x^2}\right) = -\frac{f^3\ C_{11}^{\rm face}}{12}\ \frac{{\rm d}^2 w}{{\rm d}x^2} = M_{xx}^{\rm botface}$$

In the core, the resultant moment is

$$M_{xx}^{\rm core} := \int_{-h}^{h} z\ \sigma_{xx}^{\rm core}\ {\rm d}z = 0$$

The total bending moment in the beam is

$$M = N_{xx}^{\rm topface}\ (2h + f) + 2\ M_{xx}^{\rm topface}$$

or,

$$M = -\frac{f(2h+f)^2}{2}\ C_{11}^{\rm face}\ \frac{{\rm d}^2 w_b}{{\rm d}x^2} - \frac{f^3}{6}\ C_{11}^{\rm face}\ \frac{{\rm d}^2 w}{{\rm d}x^2}$$

The shear force Q_x in the core is defined as

$$Q_x^{\rm core} = \kappa \int_{-h}^{h} \sigma_{xz}\ dz = \tfrac{\kappa(2h+f)}{2}\ C_{55}^{\rm core}\ \frac{{\rm d}w_s}{{\rm d}x}$$

where κ is a shear correction coefficient. The shear force in the facesheets can be computed from the bending moments using the relation

$$Q_x^{\rm face} = \frac{{\rm d}M_{xx}^{\rm face}}{{\rm d}x}$$

or,

$$Q_x^{\rm face} = -\frac{f^3\ C_{11}^{\rm face}}{12}\ \frac{{\rm d}^3 w}{{\rm d}x^3}$$

For thin facesheets, the shear force in the facesheets is usually ignored.

Bending and shear stiffness

The bending stiffness of the sandwich beam is given by

$$D^{\text{beam}} = -M/\tfrac{\mathrm{d}^2 w}{\mathrm{d}x^2}$$

From the expression for the total bending moment in the beam, we have

$$M = -\frac{f(2h+f)^2}{2}\,C_{11}^{\text{face}}\,\frac{\mathrm{d}^2 w_b}{\mathrm{d}x^2} - \frac{f^3}{6}\,C_{11}^{\text{face}}\,\frac{\mathrm{d}^2 w}{\mathrm{d}x^2}$$

For small shear deformations, the above expression can be written as

$$M \approx -\frac{f[3(2h+f)^2+f^2]}{6}\,C_{11}^{\text{face}}\,\frac{\mathrm{d}^2 w}{\mathrm{d}x^2}$$

Therefore, the bending stiffness of the sandwich beam (with $f \ll 2h$) is given by

$$D^{\text{beam}} \approx \frac{f[3(2h+f)^2+f^2]}{6}\,C_{11}^{\text{face}} \approx \frac{f(2h+f)^2}{2}\,C_{11}^{\text{face}}$$

and that of the facesheets is

$$D^{\text{face}} = \frac{f^3}{12}\,C_{11}^{\text{face}}$$

The shear stiffness of the beam is given by

$$S^{\text{beam}} = Q_x/\tfrac{\mathrm{d}w_s}{\mathrm{d}x}$$

Therefore the shear stiffness of the beam, which is equal to the shear stiffness of the core, is

$$S^{\text{beam}} = S^{\text{core}} = \frac{\kappa(2h+f)}{2}\,C_{55}^{\text{core}}$$

Relation between bending and shear deflections

A relation can be obtained between the bending and shear deflections by using the continuity of tractions between the core and the facesheets. If we equate the tractions directly we get

$$n_x\ \sigma_{xx}^{\text{face}} = n_z\ \sigma_{zx}^{\text{core}}$$

At both the facesheet-core interfaces $n_x = 1$ but at the top of the core $n_z = 1$ and at the bottom of the core $n_z = -1$. Therefore, traction continuity at $z = \pm h$leads to

$$2fh\ C_{11}^{\text{face}}\ \frac{\mathrm{d}^2 w_s}{\mathrm{d}x^2} - (2h+f)\ C_{55}^{\text{core}}\ \frac{\mathrm{d}w_s}{\mathrm{d}x} = 4h^2\ C_{11}^{\text{face}}\ \frac{\mathrm{d}^2 w_b}{\mathrm{d}x^2}$$

The above relation is rarely used because of the presence of second derivatives of the shear deflection. Instead it is assumed that

$$n_z\ \sigma_{zx}^{\text{core}} = \frac{\mathrm{d}N_{xx}^{\text{face}}}{\mathrm{d}x}$$

which implies that

$$\frac{\mathrm{d}w_s}{\mathrm{d}x} = -2fh\ \left(\frac{C_{11}^{\text{face}}}{C_{55}^{\text{core}}}\right)\ \frac{\mathrm{d}^3 w_b}{\mathrm{d}x^3}$$

Governing equations

Using the above definitions, the governing balance equations for the bending moment and shear force are

$$\begin{aligned} M &= D^{\text{beam}}\ \frac{\mathrm{d}^2 w_s}{\mathrm{d}x^2} - \left(D^{\text{beam}} + 2D^{\text{face}}\right)\ \frac{\mathrm{d}^2 w}{\mathrm{d}x^2} \\ Q &= S^{\text{core}}\ \frac{\mathrm{d}w_s}{\mathrm{d}x} - 2D^{\text{face}}\ \frac{\mathrm{d}^3 w}{\mathrm{d}x^3} \end{aligned}$$

We can alternatively express the above as two equations that can be solved for w and w_s as

$$\begin{aligned} &\left(\frac{2D^{\text{face}}}{S^{\text{core}}}\right)\frac{\mathrm{d}^4 w}{\mathrm{d}x^4} - \left(1 + \frac{2D^{\text{face}}}{D^{\text{beam}}}\right)\frac{\mathrm{d}^2 w}{\mathrm{d}x^2} + \left(\frac{1}{S^{\text{core}}}\right)\ \frac{\mathrm{d}Q}{\mathrm{d}x} = \frac{M}{D^{\text{beam}}} \\ &\left(\frac{D^{\text{beam}}}{S^{\text{core}}}\right)\frac{\mathrm{d}^3 w_s}{\mathrm{d}x^3} - \left(1 + \frac{D^{\text{beam}}}{2D^{\text{face}}}\right)\frac{\mathrm{d}w_s}{\mathrm{d}x} - \frac{1}{S^{\text{core}}}\ \frac{\mathrm{d}M}{\mathrm{d}x} = -\left(1 + \frac{D^{\text{beam}}}{2D^{\text{face}}}\right)\frac{Q}{S^{\text{core}}} \end{aligned}$$

Using the approximations

$$Q \approx \frac{\mathrm{d}M}{\mathrm{d}x} ~;~~ q \approx \frac{\mathrm{d}Q}{\mathrm{d}x}$$

where *q* is the intensity of the applied load on the beam, we have

$$\left(\frac{2D^{\text{face}}}{S^{\text{core}}}\right)\frac{\mathrm{d}^4w}{\mathrm{d}x^4} - \left(1 + \frac{2D^{\text{face}}}{D^{\text{beam}}}\right)\frac{\mathrm{d}^2w}{\mathrm{d}x^2} = \frac{M}{D^{\text{beam}}} - \frac{q}{S^{\text{core}}}$$
$$\left(\frac{D^{\text{beam}}}{S^{\text{core}}}\right)\frac{\mathrm{d}^3w_s}{\mathrm{d}x^3} - \left(1 + \frac{D^{\text{beam}}}{2D^{\text{face}}}\right)\frac{\mathrm{d}w_s}{\mathrm{d}x} = -\left(\frac{D^{\text{beam}}}{2D^{\text{face}}}\right)\frac{Q}{S^{\text{core}}}$$

Several techniques may be used to solve this system of two coupled ordinary differential equations given the applied load and the applied bending moment and displacement boundary conditions.

Temperature dependent alternative form of governing equations

Assuming that each partial cross section fulfills Bernoulli's hypothesis, the balance of forces and moments on the deformed sandwich beam element can be used to deduce the bending equation for the sandwich beam.

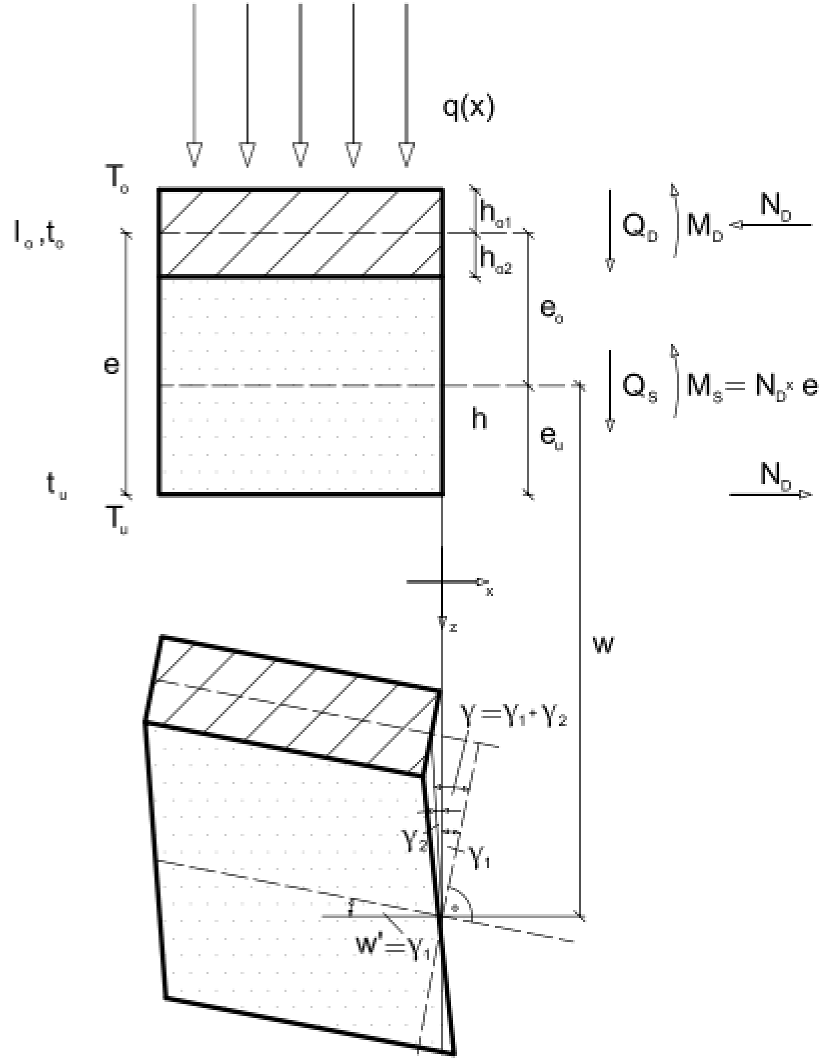


Figure 1 - Equilibration of a deflected sandwich beam under temperature load and burden in comparison with the undeflected cross section

The stress resultants and the corresponding deformations of the beam and of the cross section can be seen in Figure 1. The following relationships can be derived using the theory of linear elasticity:

$$M^{\text{core}} = D^{\text{beam}}\left(\frac{\mathrm{d}\gamma_2}{\mathrm{d}x} + \vartheta\right) = D^{\text{beam}}\left(\frac{\mathrm{d}\gamma}{\mathrm{d}x} - \frac{\mathrm{d}^2 w}{\mathrm{d}x^2} + \vartheta\right)$$

$$M^{\text{face}} = -D^{\text{face}}\frac{\mathrm{d}^2 w}{\mathrm{d}x^2}$$

$$Q^{\text{core}} = S^{\text{core}}\gamma$$

$$Q^{\text{face}} = -D^{\text{face}}\frac{\mathrm{d}^3 w}{\mathrm{d}x^3}$$

where

w	transverse displacement of the beam	
γ	Average shear strain in the sandwich	$\gamma = \gamma_1 + \gamma_2$
γ_1	Rotation of the facesheets	$\gamma_1 = \frac{\mathrm{d}w}{\mathrm{d}x}$
γ_2	Shear strain in the core	
M^{core}	Bending moment in the core	
D^{beam}	Bending stiffness of the sandwich beam	
M^{face}	Bending moment in the facesheets	
D^{face}	Bending stiffness of the facesheets	
Q^{core}	Shear force in the core	
Q^{face}	Shear force in the facesheets	
S^{core}	Shear stiffness of the core	
ϑ	Additional bending as a consequence of a temperature drop	$\vartheta = \frac{\alpha(T_o - T_u)}{e}$
α	Temperature coefficient of expansion of the converings	

Superposition of the equations for the facesheets and the core leads to the following equations for the total shear force *Q* and the total bending moment *M*:

$$S^{\text{core}}\gamma - D^{\text{face}}\frac{\mathrm{d}^3 w}{\mathrm{d}x^3} = Q \qquad (1)$$

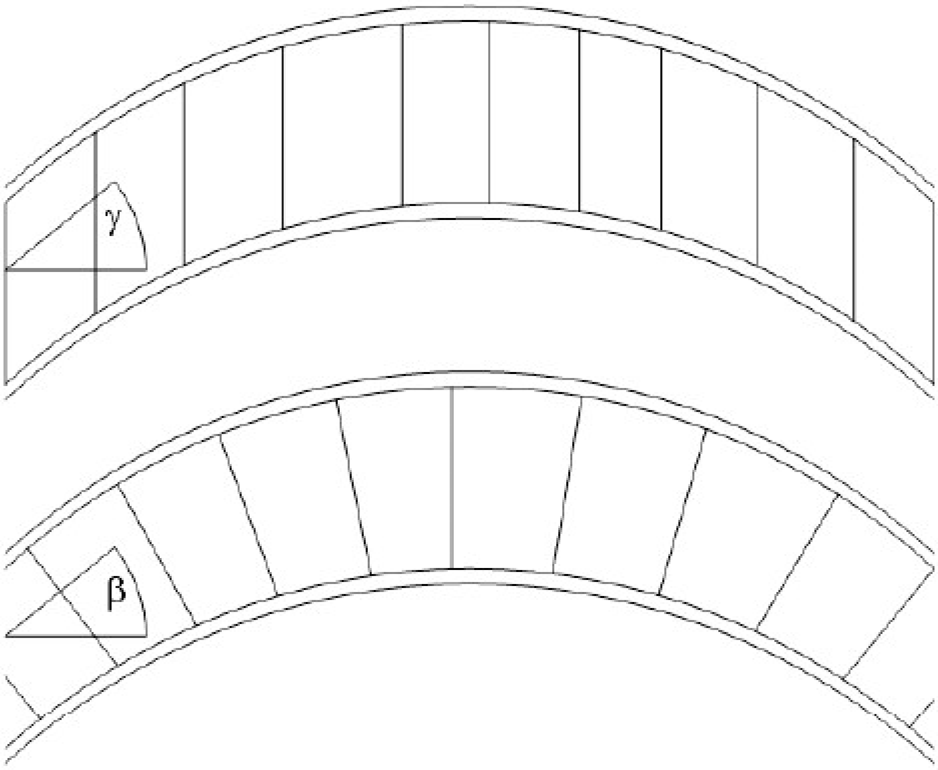
$$D^{\text{beam}}\left(\frac{\mathrm{d}\gamma}{\mathrm{d}x} + \vartheta\right) - \left(D^{\text{beam}} + D^{\text{face}}\right)\frac{\mathrm{d}^2 w}{\mathrm{d}x^2} = M \qquad (2)$$

We can alternatively express the above as two equations that can be solved for *w* and γ, i.e.,

$$\left(\frac{D^{\text{face}}}{S^{\text{core}}}\right)\frac{\mathrm{d}^4 w}{\mathrm{d}x^4} - \left(1 + \frac{D^{\text{face}}}{D^{\text{beam}}}\right)\frac{\mathrm{d}^2 w}{\mathrm{d}x^2} = \frac{M}{D^{\text{beam}}} - \frac{q}{S^{\text{core}}} - \vartheta$$

$$\left(\frac{D^{\text{beam}}}{S^{\text{core}}}\right)\frac{\mathrm{d}^2 \gamma}{\mathrm{d}x^2} - \left(1 + \frac{D^{\text{beam}}}{D^{\text{face}}}\right)\gamma = -\left(\frac{D^{\text{beam}}}{D^{\text{face}}}\right)\frac{Q}{S^{\text{core}}}$$

Solution approaches



Shear and bending deformation of a sandwich composite beam

The bending behavior and stresses in a continuous sandwich beam can be computed by solving the two governing differential equations.

Analytical approach

For simple geometries such as double span beams under uniformly distributed loads, the governing equations can be solved by using appropriate boundary conditions and using the superposition principle. Such results are listed in the standard DIN EN 14509:2006(Table E10.1). Energy methods may also be used to compute solutions directly.

Numerical approach

The differential equation of sandwich continuous beams can be solved by the use of numerical methods such as finite differences and finite elements. For finite differences Berner recommends a two-stage approach. After solving the differential equation for the normal forces in the cover sheets for a single span beam under a given load, the energy method can be used to expand the approach for the calculation of multi-span beams. Sandwich continuous beam with flexible cover sheets can also be laid on top of each other when using this technique. However, the cross-section of the beam has to be constant across the spans.

A more specialized approach recommended by Schwarze involves solving for the homogeneous part of the governing equation exactly and for the particular part approximately. Recall that the governing equation for a sandwich beam is

$$\left(\frac{2D^{\text{face}}}{S^{\text{core}}}\right)\frac{\mathrm{d}^4 w}{\mathrm{d}x^4} - \left(1 + \frac{2D^{\text{face}}}{D^{\text{beam}}}\right)\frac{\mathrm{d}^2 w}{\mathrm{d}x^2} = \frac{M}{D^{\text{beam}}} - \frac{q}{S^{\text{core}}}$$

If we define

$$\alpha := \frac{2D^{\text{face}}}{D^{\text{beam}}}~;\quad \beta := \frac{2D^{\text{face}}}{S^{\text{core}}}~;\quad W(x) := \frac{\mathrm{d}^2 w}{\mathrm{d}x^2}$$

we get

$$\frac{\mathrm{d}^2 W}{\mathrm{d}x^2} - \left(\frac{1+\alpha}{\beta}\right)~W = \frac{M}{\beta D^{\text{beam}}} - \frac{q}{D^{\text{face}}}$$

Schwarze uses the general solution for the homogeneous part of the above equation and a polynomial approximation for the particular solution for sections of a sandwich beam. Interfaces between sections are tied together by matching boundary conditions. This approach has been used in the open source code swe2.

Practical Importance

Results predicted by linear sandwich theory correlate well with the experimentally determined results. The theory is used as a basis for the structural report which is needed for the construction of large industrial and commercial buildings which are clad with sandwich panels. Its use is explicitly demanded for approvals and in the relevant engineering standards.

Chapter- 9

Pykrete

A slab of pykrete

Pykrete is made of 14 percent sawdust and 86 percent water by weight

Pykrete is a composite material made of approximately 14 percent sawdust or some other form of wood pulp (such as paper) and 86 percent ice by weight. Its use was proposed during World War II by Geoffrey Pyke to the British Royal Navy as a candidate material for making a huge, unsinkable aircraft carrier. Pykrete has some interesting properties, notably its relatively slow melting rate (due to low thermal conductivity), and its vastly improved strength and toughness over unmodified (crystalline) ice, actually closer to concrete.

Pykrete is slightly more difficult to form than concrete, as it expands during the freezing process, but can be repaired and maintained from the sea's most abundant raw material: water. The mixture can be moulded into any shape and frozen, and it will be extremely tough and durable, as long as it is kept at or below freezing.

History

Geoffrey Pyke managed to convince Lord Mountbatten of the worth of his project (actually prior to the invention of pykrete) some time around 1942, and trials were made in two locations in Alberta in Canada. The idea for a ship made of ice impressed the United States and Canada enough that a 60-foot (18 m)-long, 1,000-ton ship was built in one month on Patricia Lake in the Canadian Rockies. It was, however, constructed using plain ice (from the lake), before pykrete was considered. It took slightly more than an entire summer to melt.

Plain ice proved to be insufficiently strong. Pyke learned from a report by Herman Mark and his assistant that ice made from water mixed with wood fibres formed a strong solid mass— much stronger than pure water ice. Max Perutz later recalled:

Then, one day, Pyke handed me a report that he said he found hard to understand. It was by Herman Mark, my former professor of physical chemistry in Vienna, who had lost his post there when the Nazis overran Austria, and found a haven at the Polytechnic Institute of Brooklyn. As an expert on plastics, he knew that many of them were brittle when pure, but could be toughened by embedding fibres such as cellulose in them, just as concrete can be reinforced with steel wires. Mark and his assistant, Walter P. Hohenstein, stirred a little cotton wool or wood pulp—the raw material of newsprint—into water before they froze it, and found that these additions strengthened the ice dramatically.

When I had read their report, I advised my superiors to scrap our experiments with pure ice and set up a laboratory for the manufacture and testing of reinforced ice. Combined Operations requisitioned a large meat store five floors underground beneath Smithfield Market, which lies within sight of St. Paul's Cathedral, and ordered some electrically heated suits, of the type issued to airmen, to keep us warm at 0 °C (32 °F). They detailed some young commandos to work as my technicians, and I invited Kenneth Pascoe, who was then a physics student and later became a lecturer in engineering at Cambridge, to come and help me. We built a big wind tunnel to freeze the mush of wet wood pulp, and sawed the reinforced ice into blocks. Our tests soon confirmed Mark and Hohenstein's results. Blocks of ice containing as little as four percent wood pulp were weight for weight as strong as concrete; in honor of the originator of the project, we called this reinforced ice "pykrete". When we fired a rifle bullet into an upright block of pure ice two feet square and one foot thick, the block shattered; in pykrete the bullet made a little crater and was embedded without doing any damage. My stock rose, but no one would tell me what pykrete was needed for, except that it was for Project Habakkuk.

—*I Wish I'd Made You Angry Earlier*, *Perutz, Max*

Perutz would later learn that Project Habakkuk was the plan to build an enormous aircraft carrier, actually more of a floating island than a ship in the traditional sense. The experiments of Perutz and his collaborators in Smithfield Meat Market in the City of London took place in great secrecy behind a screen of animal carcasses. The tests confirmed that pykrete is much stronger than pure ice and does not shatter, but also that it sags under its own weight at temperatures higher than -15 C.

Mountbatten’s reaction to the breakthrough is recorded by Pyke's biographer David Lampe:

What happened next was explained several years after the war by Lord Mountbatten in a widely-quoted after-dinner speech. "I was sent to Chequers to see the Prime Minister and was told he was in his bath. I said, 'Good, that's exactly where I want him to be.' I nipped up the stairs and called out to him, 'I have a block of a new material which I would like to put in your bath.' After that he suggested that I should take it to the Quebec Conference."

The demonstration in Churchill's steaming bath had been most dramatic. After the outer film of ice on the small pykrete cube had melted, the freshly exposed wood pulp kept the remainder of the block from thawing.

—*Pyke, the Unknown Genius*, *Lampe, David*

Another tale is that at the Quebec Conference of 1943 Mountbatten brought a block of pykrete along to demonstrate its potential to the entourage of admirals and generals who had come along with Winston Churchill and Franklin D. Roosevelt. Mountbatten entered the project meeting with two blocks and placed them on the ground. One was a normal ice block and the other was pykrete. He then drew his service pistol and shot at the first block. It shattered and splintered. Next, he fired at the pykrete to give an idea of the resistance of that kind of ice to projectiles. The bullet ricocheted off the block, grazing the trouser leg of Admiral Ernest King and ending up in the wall. According to Perutz's own account, however, the incident of a ricochetting bullet hitting an Admiral actually happened much earlier in London and the gun was fired by someone on the project—not Mountbatten.

Despite these tests, the main Project Habakkuk was never put into action due to limitations in funds and the belief that the tides of the war were beginning to turn in favour of the Allies using more conventional methods.

According to the memoirs of British General Ismay:

A good deal of consideration, much of it highly technical, was also given to the feasibility of building floating platforms which could either be used by fighters to support opposed landings until such time as airfields ashore were available, or act as staging points for ferrying aircraft over long distances. The idea as originally conceived by a member of Combined Operations staff, and vehemently supported by Mountbatten, was that these floating platforms should be constructed out of icebergs. They would be provided with engines which would enable them to steam at slow speed, and with refrigeration plants to prevent them melting. They would be unsinkable. The whole thing seemed completely fantastic, but the idea was not abandoned without a great deal of investigation. Various alternative methods of construction were then considered by the

United States naval authorities, but in the end there was general agreement that carriers and auxiliary carriers would serve the same purpose more effectively."
—*The Memoirs of Lord Ismay*, *Ismay, General Lord*

Since WWII pykrete has remained a scientific curiosity, unexploited by research or construction of any significance. In 1985, pykrete was considered for a quay in Oslo harbour.

New concepts for pykrete however crop up occasionally among architects, engineers and futurists, usually regarding its potential for mammoth offshore construction or its improvement by applying super-strong materials such as synthetic composites or Kevlar.

Durability

The durability of pykrete is up for debate. It is often asserted that pykrete has a compressive strength of greater than 3,000 psi (21 MPa) so a very short 1 in (25 mm) column could support the weight of a typical car. However, no published figures support this. Perutz himself gives a value of around 1,100 psi (7.6 MPa).

A September 1943 proposal for making smaller pykrete vessels included the following table of characteristics:

Comparative properties of materials

Mechanical properties	**Ice**	**Concrete**	**Pykrete**
Crushing strength [MPa]	3.447	17.24	7.584
Tensile strength [MPa]	1.103	1.724	4.826
Density [kg/m^3]	910	2500	980