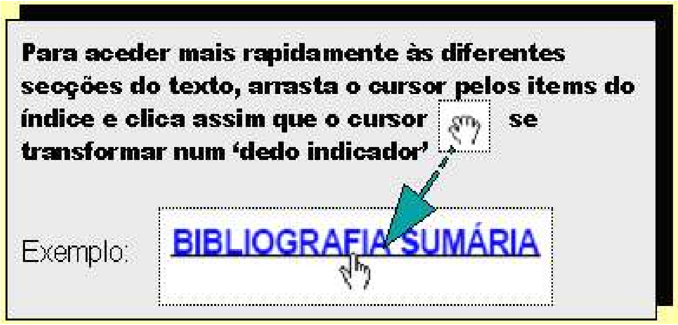
Alfred Swenson and Pao-Chi Chang (Britannica)

History of Building



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The History of Building Construction

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Introduction

The techniques and industry involved in the assembly and erection of structures, primarily those used to provide shelter.

Building construction is an ancient human activity. It began with the purely functional need for a controlled environment to moderate the effects of climate. Constructed shelters were one means by which human beings were able to adapt themselves to a wide variety of climates and become a global species.

Human shelters were at first very simple and perhaps lasted only a few days or months. Over time, however, even temporary structures evolved into such highly refined forms as the igloo. Gradually more durable structures began to appear, particularly after the advent of agriculture, when people began to stay in one place for long periods. The first shelters were dwellings, but later other functions, such as food storage and ceremony, were housed in separate buildings. Some structures began to have symbolic as well as functional value, marking the beginning of the distinction between architecture and building.

The history of building is marked by a number of trends. One is the increasing durability of the materials used. Early building materials were perishable, such as leaves, branches, and animal hides. Later, more durable natural materials such as clay, stone, and timber, and, finally, synthetic materials, such as brick, concrete, metals, and plastics?were used. Another is a quest for buildings of ever greater height and span; this was made possible by the development of stronger materials and by knowledge of how materials behave and how to exploit them to greater advantage. A third major trend involves the degree of control exercised over the interior environment of buildings: increasingly precise regulation of air temperature, light and sound levels, humidity, odours, air speed, and other factors that affect human comfort has been possible. Yet another trend is the change in energy available to the construction process, starting with human muscle power and developing toward the powerful machinery used today.

The present state of building construction is complex. There is a wide range of building products and systems which are aimed primarily at groups of building types or markets. The design process for buildings is highly organized and draws upon research establishments that study material properties and performance, code officials who adopt and enforce safety standards, and design professionals who determine user needs and design a building to meet those needs. The construction process is also highly organized; it includes the manufacturers of building products and systems, the craftsmen who assemble them on the building site, the contractors who employ and coordinate the work of the craftsmen, and consultants who specialize in such aspects as construction management, quality control, and insurance.

Building construction today is a significant part of industrial culture, a manifestation of its diversity and complexity and a measure of its mastery of natural forces, which can produce a widely varied built environment to serve the diverse needs of society. This article first traces the history of building construction, then surveys its development at the present time. For treatment of the aesthetic considerations of building design, see architecture. For further treatment of historical development, see African arts; architecture, history of; Central Asian arts; East Asian arts; Egyptian arts; Islamic arts; South Asian arts; and Southeast Asian arts.

Primitive building: the Stone Age

The hunter-gatherers of the late Stone Age, who moved about a wide area in search of food, built the earliest temporary shelters that appear in the archaeological record. Excavations at a number of sites in Europe dated to before 12,000 BC show circular rings of stones that are believed to have formed part of such shelters. They may have braced crude huts made of wooden poles or have weighted down the walls of tents made of animal skins, presumably supported by central poles.

A tent illustrates the basic elements of environmental control that are the concern of building construction. The tent creates a membrane to shed rain and snow; cold water on the human skin absorbs body heat. The membrane reduces wind speed as well; air over the human skin also promotes heat loss. It controls heat transfer by keeping out the hot rays of the sun and confining heated air in cold weather. It also blocks out light and provides visual privacy. The membrane must be supported against the forces of gravity and wind; a structure is necessary. Membranes of hides are strong in tension (stresses imposed by stretching forces), but poles must be added to take compression (stresses imposed by compacting forces). Indeed, much of the history of building construction is the search for more sophisticated solutions to the same basic problems that the tent was set out to solve. The tent has continued in use to the present. The Saudi Arabian goats' hair tent, the Mongolian yurt with its collapsible wooden frame and felt coverings, and the American Indian tepee with its multiple pole supports and double membrane are more refined and elegant descendants of the crude shelters of the early hunter-gatherers.

The agricultural revolution, dated to about 10,000 BC, gave a major impetus to building construction. People no longer traveled in search of game or followed their herds but stayed in one place to tend their fields. Dwellings began to be more permanent. Archaeological records are scanty, but in the Middle East are found the remains of whole villages of round dwellings called tholoi, whose walls are made of packed clay; all traces of roofs have disappeared. In Europe, tholoi were built of dry-laid stone with domed roofs; there are still surviving examples (of more recent construction) of these beehive structures in the Alps. In later Middle Eastern tholoi a rectangular antechamber or entrance hall appeared, attached to the main circular chamber?the first examples of the rectangular plan form in building. Still later the circular form was dropped in favour of the rectangle as dwellings were divided into more rooms and more dwellings were placed together in settlements. The tholoi marked an important step in the search for durability; they were the beginning of masonry construction.

Evidence of composite building construction of clay and wood, the so-called wattle-and-daub method, is also found in Europe and the Middle East. The walls were made of small saplings or reeds, which were easy to cut with stone tools. They were driven into the ground, tied together laterally with vegetable fibres, and then plastered over with wet clay to give added rigidity and weatherproofing. The roofs have not survived, but the structures were probably covered with crude thatch or bundled reeds. Both round and rectangular forms are found, usually with central hearths.

Heavier timber buildings also appeared in Neolithic cultures, although the difficulties of cutting large trees with stone tools limited the use of sizable timbers to frames. These frames were usually rectangular in plan, with a central row of columns to support a ridgepole and matching rows of columns along the long walls; rafters were run from the ridgepole to the wall beams. The lateral stability of the frame was achieved by burying the columns deep in the ground; the ridgepole and rafters were then tied to the columns with vegetable fibres. The usual roofing material was thatch: dried grasses or reeds tied together in small bundles, which in turn were tied in an overlapping pattern to the light wooden poles that spanned between the rafters. Horizontal thatched roofs leak rain badly, but, if they are placed at the proper angle, the rainwater runs off before it has time to soak through. Primitive builders soon determined the roof pitch that would shed the water but not the thatch. Many types of infill were used in the walls of these frame houses, including clay, wattle and daub, tree bark (favoured by American Woodland Indians), and thatch. In Polynesia and Indonesia, where such houses are still built, they are raised above the ground on stilts for security and dryness; the roofing is often made of leaves and the walls are largely open to allow air movement for natural cooling. Another variation of the frame was found in Egypt and the Middle East, where timbers were substituted for bundles of reeds.

Bronze Age and early urban cultures

It was the cultures of the great river valleys?including the Nile, the Tigris and Euphrates, the Indus, and the Huang Ho?with their intensive agriculture based on irrigation, that developed the first communities large enough to be called cities. These cities were built with a new building technology, based on the clay available on the riverbanks. The packed clay walls of earlier times were replaced by those constructed of prefabricated units: mud bricks. This represented a major conceptual change from the free forms of packed clay to the geometric modulation imposed by the rectangular brick, and the building plans too became strictly rectangular.

Bricks were made from mud and straw formed in a four-sided wooden frame, which was removed after evaporation had sufficiently hardened the contents. The bricks were then thoroughly dried in the sun. The straw acted as reinforcing to hold the brick together when the inevitable shrinkage cracks appeared during the drying process. The bricks were laid in walls with wet mud mortar or sometimes bitumen to join them together; openings were apparently supported by wooden lintels. In the warm, dry climates of the river valleys, weathering action was not a major problem, and the mud bricks were left exposed or covered with a layer of mud plaster. The roofs of these early urban buildings have disappeared, but it seems likely that they were supported by timber beams and were mostly flat, since there is little rainfall in these areas. Such mud brick or adobe construction is still widely used in the Middle East, Africa, Asia, and Latin America.

@ Brick walls and corbel vault at the entrance to the tomb chamber of Ur-nammu in the royal mausoleum

Later, about 3000 BC in Mesopotamia, the first fired bricks appeared. Ceramic pottery had been developing in these cultures for some time, and the techniques of kiln-firing were applied to bricks, which were made of the same clay. Because of their cost in labour and fuel, fired bricks were used at first only in areas of greater wear, such as pavements or the tops of walls subject to weathering. They were used not only in buildings but also to build sewers to drain wastewater from cities. It is in the roofs of these underground drains that the first surviving true arches in brick are found, a humble beginning for what would become a major structural form. Corbel vaults and domes made of limestone rubble appeared at about the same time in Mesopotamian tombs (Figure 1). Corbel vaults are constructed of rows of masonry placed so that each row projects slightly beyond the one below, the two opposite walls thus meeting at the top. The arch and the vault may have been used in the roofs and floors of other buildings, but no examples have survived from this period. The well-developed masonry technology of Mesopotamia was used to build large structures of great masses of brick, such as the temple at Tepe Gawra and the ziggurats at Ur and Borsippa (Birs Nimrud), which were up to 26 metres (87 feet) high. These symbolic buildings marked the beginnings of architecture in this culture.

The development of bronze, and later iron, technology in this period led to the making of metal tools for working wood, such as axes and saws. Less effort was thus required to fell and work large trees. This led in turn to new developments in building technics; timbers were cut and shaped extensively, hewed into square posts, sawed into planks, and split into shingles. Log cabin construction appeared in the forested areas of Europe, and timber framing became more sophisticated. Although the excavated remains are fragmentary, undoubtedly major advances were made in timber technology in this period; some of the products, such as the sawed plank and the shingle, are still used today.

Stone construction in Egypt

Like the other great river valley cultures, Egypt built its cities with mud brick; fired brick did not appear there until Roman times. Timber was used sparingly, for it was never abundant. It was used mainly in roofs, where it was heavily supplemented by reeds. Only a few royal buildings were built with full timber frames.

It was against this drab background of endless mud brick houses that a new technology of cut-stone construction emerged in the temples and pyramids of the 4th dynasty (c. 2575?c. 2465 BC). Egypt, unlike Mesopotamia or the Indus valley, had excellent deposits of stone exposed above ground; limestone, sandstone, and granite were all available. But the extracting, moving, and working of stone was a costly process, and the quarrying of stone was a state monopoly. Stone emerged as an elite construction material used only for important state buildings.

The Egyptians developed cut stone for use in royal mortuary buildings not only for its strength but also for its durability. It seemed the best material to offer eternal protection to the pharaoh's ka, the vital force he derived from the sun-god and through which he ruled. Thus stone had both a functional and symbolic significance.

Within the long tradition of brick masonry, stone construction appeared abruptly, with little transition. The brick mastaba tombs of the early kings and nobles suddenly gave way to the stone technics of King Djoser's ceremonial complex at Saqqarah, the construction of which is associated with his adviser and builder Imhotep. It is a structure of somewhat curious and uncertain forms but of great elegance in execution and detail. It consists mostly of massive limestone walls that enclose a series of interior courtyards. The walls have convoluted surfaces, which recall the mastaba tombs, with dummy doors, and there are even whole dummy buildings of solid stone. The complex has a large entrance hall with a roof supported by massive stone lintels that rest on rows of short wing walls projecting from the enclosing walls. There are no free-standing columns, but incipient fluted columns appear at the ends of the wing walls and engaged 3/4-columns project from the walls of the courtyards. The complex also contains the first pyramid, created from successively smaller mastabas. All these elements are built of small stones, which could be handled by one or two men. It represents a technology that was already highly developed, involving elaborate methods of quarrying, transporting, and working stone.

The construction process began at the quarries. Most of them were open-faced, although in some cases tunnels were extended several hundred metres into cliffs to reach the best quality stone. For extracting sedimentary rock, the chief tool was the mason's pick with a 2.5-kilogram metal head and a 45-centimetre haft. With these picks vertical channels as wide as a man were cut around rectangular blocks, exposing five faces. The final separation of the sixth face was accomplished by drilling rows of holes into the rock with metal bow drills. Wooden wedges were driven into the holes to fill them completely. The wedges were doused with water, which they absorbed and which caused them to expand, breaking the stone free from its bed. In the extraction of igneous rock such as granite, which is much harder and stronger than limestone, the mason's pick was supplemented by balls of dolerite weighing up to 5 kilograms, which were used to break the rock by beating and pounding. Granite was also drilled and sawed with the help of abrasives, and expanding wooden wedges were used in splitting.

The Egyptians were able to move blocks weighing up to 1,000,000 kilograms from quarries to distant building sites. This was an amazing accomplishment, as their only machinery was levers and crude wooden sledges worked by masses of men and draft animals. There were no wheeled vehicles before 1500 BC, and they were never widely used in building. Most quarries were near the Nile, however, and boats were also extensively used in transporting stone.

At the building site the rough stones were precisely finished to their final forms, with particular attention to their exposed faces. This was done with metal chisels and mallets; squares, plumb bobs, and straightedges were used to check the accuracy of the work. These tools remained standard until the 19th century. After the first appearance of small stones at Saqqarah, their size began to increase until they attained the cyclopean scale usually associated with Egyptian masonry at about the time of the building of the pyramids. In spite of the heavy loads that stone structures created, foundations were of a surprisingly shoddy and improvised character, made of small blocks of poor quality stone. Not until the 25th dynasty (c.750? - 656 BC) were important buildings placed on a below-grade (underground) platform of masonry several metres thick.

The Egyptians possessed no lifting machinery to raise stones vertically. It is generally thought that the laying of successive courses of masonry was accomplished with earth or mud brick ramps, over which the stones were dragged to their places in the walls by animal and human muscle power. Later, as the ramps were removed, they served as platforms for the masons to apply the final finishes to the stone surfaces. The remains of such ramps can still be seen at unfinished temples that were begun in the Ptolemaic period. The stones were usually laid with a bed of mortar made of gypsum, sand, and water, which perhaps acted more as a lubricant to push the stone into place than as a bonding agent. There was also limited use of metal dovetail anchors between blocks.

The great Pyramids of Giza, the tallest of which rose to a height of 147 metres (481 feet), are a marvelous technological achievement, and their visual impact is stunning even today; it was not until the 19th century that taller structures would be built. But they also represent a dead end in massive stone construction, which soon moved in the direction of lighter and more flexible stone frames and the creation of larger interior spaces. The free-standing stone column supporting stone beams appeared for the first time in the royal temples associated with the pyramids of about 2600 BC. Square granite columns carrying heavy granite lintels spanned three to four metres (10 to 13 feet); the spaces between the lintels were roofed by massive granite slabs. In these structures the abstract notion of the timber frames of the early royal buildings was translated into stone.

Although stone is more durable than timber, it is quite different in structural strength. Stone is much stronger in compression than timber but is weaker in tension. For this reason, stone works well for columns, which could be made very high?for example, 24 metres (80 feet) in the great temple of Amon-Re at Karnak. But stone lintels spanning between columns are limited by the tension they develop on their bottom surfaces; their maximum span is perhaps five metres (16 feet). Thus, for longer spans, another structural form was needed to exploit the higher compressive strength of stone. But the arch, which could span a longer distance in compression, remained confined to the sewers and to the underground roofs of the tombs of minor officials. So, perhaps with the image of the timber building frame still strong in their minds, the Egyptian masons were content to explore the limitations of the analogous stone frame in a series of great temples built during the New Kingdom (1539? - 1075 BC) at Karnak and Luxor, culminating in the elegant loggias of Queen Hatshepsut's temple at Dayr al-Bahri. The paradigm of the stone-frame temple that they established would endure to the end of the classical world.

Greek and Hellenistic cultures

Use of the Egyptian stone frame diffused throughout the eastern Mediterranean after 1800 BC, and the cultures of mainland Greece were particularly attracted to it. In the Greek world of the Aegean and southern Italy, many stone-frame temples were built; some have survived to the present day in various states of preservation. They were built largely of local marble or limestone; there was no granite for huge monoliths. The basic technology was little changed from that of Egypt; the major difference was in the labour force. There were no state-mobilized masses of unskilled workers to move huge stones; there were instead small groups of skilled masons who worked independently. The building accounts of the Parthenon show that each column was built under a separate contract with a master mason. There was certainly lifting machinery for handling the blocks, although its precise description is unknown; the concealed faces of stones still have grooves and holes that engaged the ropes used to lift them into place. Metal cramps and dowels were introduced for joining stones together; mortar was almost never used. There was some experimentation with iron beams to reinforce longer spans in stone, but the maximum remained about five to six metres (16 to 20 feet). Longer spans were achieved with timber beams supported by the stone frame; the solid stone roof slabs of the great Egyptian temples could not be duplicated.

Much of the mason's effort was concentrated on the refinements of detail and optical corrections for which Greek architecture is justly famous. This same sense is also seen in the first surviving construction drawings, which were made on the unfinished surfaces of the stone walls of the Temple of Didyma. Such drawings would normally have been erased during the final finishing of the wall surfaces, and those at Didyma survived because the temple was never completed. The drawings show how the masons developed the final profiles of columns and moldings, a rare glimpse of the design processes of builders before the days of pencil and paper.

In contrast to stone technology, which remained largely unchanged from Egyptian methods, clay masonry underwent considerable development. Although mud brick remained standard for dwellings, fired brick was more widely used and began to be laid with lime mortar, a technique borrowed from stone construction. Glazed brick also appeared in this period, particularly outside the Greek world among the Babylonians and Persians, who made considerable use of it in royal palaces. A fine surviving example is the Ishtar Gate of the Palace of Nebuchadrezzar at Babylon, with a true arch spanning 7.5 metres (25 feet) and dated to 575 BC. Another major innovation was the fired clay roof tile. This was much more waterproof than thatch, and tile roofs could have the lower pitch characteristic of Greek temples. Hollow terra-cotta blocks for wall ornaments also appeared about this time, probably derived from the highly advanced pottery industry, which routinely made fired clay vessels more than one metre long.

Although stone technology remained confined to the trabeated (column-and-beam, or post-and-lintel) frame, there were a few structures that hinted at future developments. Perhaps the most spectacular building achievement of the age was the Pharos of Alexandria, the great lighthouse built for Ptolemy II in the 3rd century BC. It was a huge stone tower nearly as high as the Great Pyramid but much smaller at the base?perhaps 30 metres (100 feet) square. Within this mass of masonry was a complex system of ramps over which pack animals carried fuel for the beacon at the top. The Pharos was the first high-rise building, but the limitations of masonry structures and the lack of a rapid way of moving people vertically precluded any further development of tall buildings until the 19th century. The Pharos remained the only example of this type long after it was demolished by the Arabs beginning in the 7th century AD.

Another example of a new stone technology that was tried but not pursued further by the Greeks was the underground tombs of Mycenae, built about 1300 BC. These tombs have main chambers enclosed by pointed domes of corbeled stone construction, about 14 metres (47 feet) in diameter and 13 metres (43 feet) high. Crude versions of the corbel dome had appeared earlier in Mesopotamian tombs and the tholoi of Neolithic Europe, but in Mycenae the technics were refined and enlarged in scale. A corbel dome or arch does not develop the high compressive forces that characterize true arches and domes, which are built of radial segments of stone or brick. Thus it does not take full advantage of the great compressive strength of stone and cannot span long distances; 14 metres is near the upper limit. Greek masons did not choose to explore this type of structure; their buildings remained largely concerned with exterior forms. The Roman builders who followed them, however, exploited masonry to its full potential and created the first great interior spaces.

Roman achievements

It was from the Etruscans, who lived in the northern part of Italy, that the Romans derived much of their early building technology. The Etruscans, probably influenced by a few rare Greek examples in southern Italy, developed the true arch in stone. A late specimen of the 3rd century BC is the Porta Marzia, an arched city gateway with a span of about six metres (20 feet), in Perugia. The Etruscans also had a highly developed terra-cotta technology and made excellent fired bricks.

Masonry construction

The Romans adopted Etruscan stone construction based on the arch and built many spectacular examples of what they called opus quadratum, or structures of cut stone blocks laid in regular courses. Most of these were public works in conquered provinces, such as the late 1st-century-BC Pont du Gard, a many-arched bridge and aqueduct spanning 22 metres (72 feet) near Nîmes, in France, or the fine bridge over the Tagus River at Alcántara in Spain, with a span of almost 30 metres (100 feet), built about AD 110. Oddly enough, such long spans in stone were never applied to buildings. The surviving Roman buildings with stone arches or vaults have typical spans of only four to seven metres (15 to 25 feet); small stone domes with diameters of four to nine metres were built in Roman Syria. Such arches and domes imply the existence of sophisticated timber formwork to support them during construction, as well as advanced lifting machinery, but there are no extant records of either. Many of these structures survived the fall of the empire, and they became models for the revival of stone construction in medieval Europe, when masons again sought to build ?in the Roman manner.? The Romans also inherited the trabeated stone frame from the Greeks of southern Italy and continued to build temples and other public buildings with this type of construction into the 3rd century AD.

Brickmaking, particularly in the region of Rome itself, became a major industry and finally, under the empire, a state monopoly. Brick construction was cheaper than stone due to the economies of scale in mass production and the lower level of skill needed to put it in place. The brick arch was adopted to span openings in walls, precluding the need for lintels. Mortar was at first the traditional mixture of sand, lime, and water, but, beginning in the 2nd century BC, a new ingredient was introduced. The Romans called it pulvis puteoli after the town of Puteoli (modern Pozzuoli), near Naples, where it was first found; the material, formed in Mount Vesuvius and mined on its slopes, is now called pozzolana. When mixed with lime, pozzolana forms a natural cement that is much stronger and more weather-resistant than lime mortar alone and that will harden even under water. Pozzolanic mortars were so strong and cheap, and could be placed by labourers of such low skill, that the Romans began to substitute them for bricks in the interiors of walls; the outer wythes of bricks were used mainly as forms to lay the pozzolana into place. Finally, the mortar of lime, sand, water, and pozzolana was mixed with stones and broken brick to form a true concrete, called opus caementicium. This concrete was still used with brick forms in walls, but soon it began to be placed into wooden forms, which were removed after the concrete had hardened.

Early concrete structures

One of the earliest surviving examples of this concrete construction is the Temple of the Sybil (or Temple of Vesta) at Tivoli, built during the 1st century BC. This temple has a circular plan with a peristyle of stone columns and lintels around the outside, but the wall of the circular cella, or sanctuary room, inside is built of concrete?an uneasy confrontation of new and traditional forms of construction. An early large-scale example in Rome itself of brick-faced concrete is the plain rectangular walls of the Camp of the Praetorian Guard, built by Sejanus in AD 21?23. But the possibilities of plastic form suggested by this initially liquid material, which could easily assume curved shapes in plan and section, soon led to the creation of a series of remarkable interior spaces, spanned by domes or vaults and uncluttered by the columns required by trabeated stone construction, that showed the power of the imperial state. The first of these is the octagonal domed fountain hall of Nero's Golden House (AD 64?68), which is about 15 metres (50 feet) in diameter with a large circular opening, or oculus, in the top of the dome. The domed form was rapidly developed in a series of imperial buildings that culminated in the emperor Hadrian's Pantheon of about AD 118-128. This huge circular structure was entered from a portico of stone columns and was surmounted by a dome 43.2 metres (142 feet) in diameter, lighted by an oculus at the top. The walls supporting the dome are of brick-faced concrete six metres (20 feet) thick lightened at intervals by internal recesses; the dome is of solid concrete 1.5 metres (five feet) in average thickness and rising 43.2 metres above the floor. This magnificent structure has survived in good condition to modern times; the diameter of its circular dome remained unsurpassed until the 19th century.

Two large fragments of great concrete cross-vault buildings still survive from the late empire. The first of these is a portion of the Baths of Diocletian (c. 298-306) with a span of 26 metres (85 feet); it was converted into the church of Santa Maria degli Angeli by Michelangelo in the 16th century. The other is the Basilica of Maxentius (AD 307-312), also with a span of 26 metres. All of these buildings contained stone columns, but they were purely ornamental and could have been removed at will. The brick-faced concrete walls were left exposed on the exteriors, but the interiors were lavishly decorated with a veneer of thin slabs of coloured stone held in place by metal fasteners that engaged slots cut in the edges of the slabs, a technique still used in the 20th century. These and other great Roman public spaces spanned by concrete domes and vaults made a major advance in scale over the short spans of the stone frame.

In the late empire, concrete technology gradually disappeared, and even brickmaking ceased in western Europe. But significant developments in brick technology continued in the eastern Roman world, where the achievements of earlier periods in concrete were now duplicated in brickwork. The tomb of the emperor Galerius (now the Church of St. George) of about AD 300 at Salonika in Greece has a brick dome 24 metres (80 feet) in diameter. It probably was the model for the climactic example of late Roman building, the great church of Hagia Sophia (532-537) in Constantinople, which features a central dome spanning 32.6 metres (107 feet). Even Rome's great enemies, the Sasanian Persians, built a large brick-vaulted hall in the palace at Ctesiphon (usually identified with Khosrow I [mid-6th century] but probably a 4th-century structure) with a span of 25 metres (82 feet) by borrowing Roman methods. These late brick structures were the last triumphs of Roman building technology and would not be equaled for the next 900 years.

Timber and metal construction

The Romans also made major advances in timber technology. Reliefs on Trajan's Column show the timber lattice truss bridges used by Roman armies to cross the Danube. The truss, a hollowed-out beam with the forces concentrated in a triangulated network of linear members, was apparently a Roman invention. No evidence of their theoretical understanding of it exists, but nevertheless they were able to master the design of trusses in a practical way. A fine example is the Basilica of Constantine at Trier (AD 297?299), where timber king-post roof trusses (triangular frames with a vertical central strut) span a hall 23 metres (75 feet) wide; the present roof is a restoration, but the original must have been similar.

The notion of the truss was extended from timber to metal. Bronze trusses, running over three spans of about nine metres (30 feet) each, supported the roof of the portico of the Pantheon. The choice of bronze was probably made more for durability than strength, because Pope Urban VIII was able to remove this bronze work in 1625 (to melt it down for cannon) and replace it with timber trusses. The truss remained an isolated achievement of Roman building that would not be equaled until the Renaissance.

Metals were used extensively in Roman buildings. In addition to bronze trusses, the Pantheon had bronze doors and gilded bronze roof tiles. Lead was another material introduced by the Romans for roofing; it was waterproof and could be used with very low pitches.

Building support systems

Perhaps the most important use of lead was for pipes to supply fresh water to buildings and to remove wastewater from them (the word plumbing comes from the Latin plumbum, which means lead). The Romans provided generous water supplies for their cities; all of the supply systems worked by gravity and many of them used aqueducts and syphons. Although most people had to carry their water from public fountains, there was limited distribution of water to public buildings (particularly baths) and some private residences and apartment houses; private and semiprivate baths and latrines became fairly common. The wastewater drainage system was limited, with no treatment of sewage, which was simply discharged into a nearby river. But even these fairly modest applications of public sanitation far exceeded those of previous cultures and would not be equaled until the 19th century.

Another material that the Romans applied to buildings was glass, which had been developed by the Egyptians who used it only for jewelry and small ornamental vessels. The Romans devised many kinds of coloured glass for use in mosaics to decorate interior surfaces. They also made the first clear window glass, produced by blowing glass cylinders that were then cut and laid flat. Seneca (c. 4 BC?AD 65) described the sensation caused by the appearance of glazed sun porches in the villas near Rome. Although no Roman glass installations have survived, glass apparently became fairly common in public buildings and was even used in middle-class apartment houses in the capital.

In most Roman buildings, the central open fire remained the major source of heat?as well as annoying smoke?although the use of charcoal braziers made some improvement. A major innovation was the development of hypocaust, or indirect radiant, heating, by conducting heated air through flues in floors and walls. The heated masonry radiated a pleasantly uniform warmth, and smoke was eliminated from occupied spaces; the same method was used to heat water for baths. The Basilica of Constantine at Trier has a well-preserved example of hypocaust heating, where the stone slabs of the floor are supported on short brick columns, creating a continuous heating plenum beneath it.

Romanesque and Gothic

The disappearance of Roman power in western Europe during the 5th century led to a decline in building technology. Brickmaking became rare and was not revived until the 14th century. Pozzolanic concrete disappeared entirely, and it would not be until the 19th century that man-made cements would equal it. The use of domes and vaults in stone construction was also lost. Building technics fell to Iron Age levels, exemplified by log construction, packed clay walls, mud brick, and wattle and daub.

Advanced building technologies were developing in China in this same period during the Sui (581?618) and T'ang (618?907) dynasties. In the 3rd century BC the completion of the Great Wall, about 6,400 kilometres (4,000 miles) in length and following a sinuous path along the contours of rugged terrain, had demonstrated remarkable achievements in masonry technology, logistics, and surveying methods. The An-Chi Bridge, built about AD 610 in Hopei province, had a stone arch with a span of 37.5 metres (123 feet), far exceeding the Roman bridge at Alcántara. Extensive work was also done in the development of heavy timber framing (primarily for temples), and stone tower pagodas up to 60 metres (200 feet) high were built; fired brick was also widely used. These elements of Chinese building technology set a high standard of quality that would be maintained until the 19th century.

Stone construction

Beginning in the 9th century there were the first stirrings of the revival of stone construction in Europe; the Palatine Chapel of Charlemagne at Aachen (consecrated 805), with its octagonal segmented dome spanning 14.5 metres (47 feet), is an early example of this trend. But the Romanesque style, building ?in the Roman manner? with stone arches, vaults, and domes to span interior spaces, did not really begin until the later part of the 11th century. Vaults reappeared in such structures as the cathedral of Santiago de Compostela in Spain (begun 1078) and Saint Sernin at Toulouse (begun 1080). The cross vault raised on columns was seen again at Speyer Cathedral (1030?65, reconstructed c. 1082?1137) and Durham Cathedral (1093?1133), and the domes of St. Mark's Basilica in Venice (late 11th century) and the cathedral of Saint-Front in Périgueux (1120?1150) marked the recovery of the complete range of Roman structural forms. All these buildings were built by the Roman Catholic church, which had spread its influence throughout western Europe in this period. One contemporary chronicler wrote that the earth seemed to be ?clothing itself with a white robe of churches,? white because they were new and built of stone. From 1050 to 1350 more stone was quarried in France alone than in the whole history of ancient Egypt?enough to build 80 cathedrals, 500 large churches, and tens of thousands of parish churches. The great building campaign of medieval times has been called the ?cathedral crusade,? an equally impassioned counterpart of the great military adventures to recover the Holy Land. This vast undertaking required many masons, who worked as free craftsmen, organizing themselves into societies or guilds. They oversaw the quarrying of stone, supervised the process of apprenticeship by which new members were trained, and did all the cutting and placing of stone at the building site. The basic tools of the medieval masons were little changed from those of Egypt, but they had large saws driven by waterwheels to cut stone as well as considerable machinery for raising and moving materials. Their knowledge of technics was a closely held secret; it included the rules of proportion for overall planning and for determining the safe dimensions of structural members. One extant sketchbook of drawings, from the master mason Villard de Honnecourt, shows a keen sense of observation, a love of mechanical devices, and above all the notion of geometric form that underlay the work; but it gives only tantalizing bits of information about actual building construction. Jean Mignot, one of the master masons of Milan Cathedral, summed up their approach with the phrase ars sine scientia nihil est, ?art without science is nothing?; that is, skill in building derived from practical experience (ars) must be tempered and guided by precise principles (scientia), which were seen as being embodied in the theorems of geometry, the only science of medieval times. But with these limited means the masons were able to realize great achievements.

Romanesque masons had two patrons, church and state. The state built mostly for military purposes, and Roman stonework, once recovered, was adequate for castles and fortifications. But the church had other interests that propelled the development of stone construction in new and daring directions. St. Augustine had written that light is the most direct manifestation of God. It was this idea that led the search for ways to introduce more and more light into churches, opening ever larger windows in the walls until a new kind of diaphanous stone skeleton evolved.

The Roman-inspired circular cross vaults and arches in stone were heavy and needed heavy walls and piers to receive their thrusts; the windows they offered were small. Medieval masons found that there was a more efficient form for the arch than the classical circle; this form is a catenary curve?that is, one formed by a chain when it hangs under its own weight. But the masons' belief in geometry and the perfection of circular forms led them to approximate the catenary shape with two circular segments that met in a point at the top, the so-called Gothic arch. Such arches could be made thinner since they more efficiently channeled the compressive forces that flowed through them and allowed larger openings in the walls. The heavy piers that took the lateral thrust of the roof vaults were soon hollowed out into half arches or flying buttresses, which allowed even more light to enter the nave. To absorb the forces flowing down through the stone frame, massive foundations were required; often the volume of stone below ground was greater than that above. To further lighten the loads, the vaults themselves were made thinner by introducing ribs at the intersections of their curved surfaces, called groins. The ribs were built with supporting formwork or centring made of timber; close cooperation was needed between the carpenters and the masons. The curved surfaces of stones between the ribs were probably laid with little formwork, using only mortar; brick vaults are still built this way in the Middle East. The mortar was used not only for adhesion as a construction device but also later to check for tension cracks, which were signs of possible failure; the mortar thus served as a means of quality control to help keep the structure in compression. The naves of cathedrals were made higher to gather more light; Amiens Cathedral (begun 1220) was 42 metres (140 feet) high, and finally in 1347 Beauvais Cathedral reached the maximum height of 48 metres (157 feet), but its vaults soon collapsed and had to be rebuilt. The spans of the naves of Gothic churches remained fairly small, about 13 to 16 metres (45 to 55 feet); only a few late examples have longer spans, the greatest being 23 metres (74 feet) at Gerona Cathedral (completed 1458).

After the enthusiasm of the cathedral crusade ebbed in the 14th century and the basic fabric of most cathedrals was completed, a new element appeared to further test the skill of masons and carpenters: the spire. The spire was more a symbol of local pride than a part of the theological quest for more light, but it raised interesting technical problems. At Salisbury Cathedral the spire was built over the crossing of the nave and transept, which had not been designed to accommodate it; the tall crossing piers began to buckle under the added weight. Strainer arches had to be added between the piers to brace them against buckling; this was apparently the first time that stone columns were slender and heavily loaded enough to be observed to bend or buckle?later, such action would be a major concern in the design of metal columns. Salisbury's spire is an ingenious composite structure of stone cladding laid over a timber frame and tied together at the base with iron bands to resist spreading; it rose to a total height of 123 metres (404 feet) when it was finished in 1362. Strasbourg Cathedral added a 144-metre (475-foot) spire in 1439, and the upper limit was reached at Beauvais Cathedral in 1569 when its 157-metre (516-foot) spire was completed; the Beauvais spire collapsed in 1573 and was never rebuilt, a last sad epilogue to the cathedral crusade.

Construction in timber and brick

Timber construction underwent slow development in this period. Scandinavian stave churches of heavy timber were built in the 8th to 10th centuries, prior to the triumph of the stone church, and a few have survived to the present day. In western Europe, particularly from the 14th century onward, half-timber construction emerged as a new form of house building. The continental type had a frame of squared timbers, with vertical posts spaced about one metre apart and horizontal girts spaced at the same distance; diagonal braces were run through the outside walls for lateral stability. The roof beams spanned between the ridgepole and the walls; floor beams were supported on the walls and interior partitions. The English half-timber frame was similar, but it eliminated the horizontal girts and diagonal bracing by using closely spaced verticals about one-half metre apart. In both systems the space in the outside wall was filled with an enclosure material to impart added rigidity to the frame; brick or wattle and daub were often used. All the timbers of the frame were attached together by elaborate dovetail, or mortise-and-tenon, joints. Half-timber framing would remain the standard way of building with wood in Europe until the 19th century. There was also considerable use of heavy timber for the roofs and floors of masonry buildings, which was influenced by shipbuilding technology. A particular instance of this is the English hammer-beam roof, which was a kind of corbeled truss that could span quite long distances. The roof of King Richard II's Westminster Hall in London (1402), with a 21-metre (70-foot) span, is an excellent example of this type.

Fired brick began to be made again in Europe in the 14th century, preceded in many areas by the use of salvaged Roman brick. The 14th-century bricks were not as precise as the Roman and were often distorted in firing. Therefore, large lime-mortar joints were needed for regular course lines. Bricks became nearly standardized at something close to the present size, about 20.3 ´ 9.5 ´ 5.7 centimetres (8' 3.75' 2.25 inches), and bonding systems based on this approximately 2 : 1 proportion were developed. These bonding patterns reduced continuous vertical mortar joints, because the mortars were of substantially lower strength than the bricks and vertical joints could form planes of weakness in the walls where cracks might develop. The best bonding pattern was English bond, in which all the bricks in each course overlapped the ones below and vertical joints were entirely eliminated. Brick remained quite expensive because of the cost of the fuel needed to fire it, and it was used mainly where there was no readily available stone. In the late medieval period and mostly in northern Europe, brick was adapted to Gothic stone forms to build so-called hall churches, with naves and aisles of equal height.

Building services

Although Roman hypocaust heating disappeared with the empire, a new development in interior heating appeared in western Europe at the beginning of the 12th century: the masonry fireplace and chimney began to replace the central open fire. The large roof openings over central fires let in wind and rain, so each house had only one and larger buildings had as few as possible. Therefore, heated rooms tended to be large and semipublic, where many persons could share the fire's warmth; the roof opening did not effectively remove all the smoke, some of which remained to plague the room's occupants. The chimney did not let in much air or water and could remove most of the smoke. Although much of the heat went up the flue, it was still a great improvement, and, most significantly, it could be used to heat both small and large rooms and multistory buildings as well. Houses, particularly large ones, were broken up into smaller, more private spaces each heated by its own fireplace, a change that decisively altered the communal life-style of early medieval times.

The Renaissance

Reintroduction of dome construction

The waning of the cathedral crusade in the late 14th century led to a decline in the International Gothic style practiced by the master masons. In this period the emerging nation-states of Europe began to compete with the church as centres of power. To these new nations, the Roman Empire was the model nation-state, and it seemed appropriate that they use Roman building forms as symbols of their power?particularly the round arch, the vault, and, above all, the dome, following the powerful example of the Pantheon. From 1350 until 1750 much of building technology was focused on the domed church, which developed as a symbol not only of religious belief but also of national and urban pride. There was a conscious rejection of Gothic forms in favour of the ideological appeal of Rome. This attitude led to a split between the processes of design and construction and to the appearance of the first architects (a word derived from the Greek architekton, meaning a chief craftsman), who conceived a building's form, as opposed to the builder, who executed it. The first building in which the designer and the builder were separate persons was the Campanile, or bell tower, of the cathedral of Florence. The design was made by the painter Giotto and constructed by cathedral masons from 1334 to 1359.

The cathedral of Florence itself had been begun in the Gothic style by Arnolfo di Cambio in 1296. But in 1366 the City of Florence, following the advice of certain painters and sculptors, decided that the Gothic should no longer be used and that all new work should follow Roman forms, including an octagonal dome 42 metres (138 feet) in span to be built at the east end of the nave. The dome was not built until the early 15th century, when Filippo Brunelleschi, a goldsmith and sculptor, began to make statues for the cathedral. Gradually he became interested in the building itself and built some smaller parts of it. In about 1415 he prepared a design for the dome that he daringly proposed to build without the aid of formwork, which had been absolutely necessary in all previous Roman and Gothic construction. He built a 1 : 12 model of the dome in brick to demonstrate his method; the design was accepted and built under his supervision from 1420 to 1436. Brunelleschi was thus the first real architect to conceive the building's form and the methods to execute it and to guarantee its performance; he pointedly refused membership in both the masons' and carpenters' guilds. Brunelleschi's dome consists of two layers, an inner dome spanning the diameter and a parallel outer shell to protect it from the weather and give it a more pleasing external form. Both domes are supported by 24 stone half arches, or ribs, of circular form, 2.1 metres (seven feet) thick at the base and tapering to 1.5 metres (five feet), which meet at an open stone compression ring at the top. To resist outward thrust, tie rings of stone held together with metal cramps run horizontally between the ribs. There are also tie rings of oak timbers joined by metal connectors. The spaces between the ribs and tie rings are spanned by the inner and outer shells, which are of stone for the first 7.1 metres (23 feet) and brick above. The entire structure was built without formwork, the circular profiles of the ribs and rings being maintained by a system of measuring wires fixed at the centres of curvature. Brunelleschi obviously understood enough about the structural behaviour of the dome to know that, if it were built in horizontal layers, it would always be stable and not require timber centring. He also designed elaborate wooden machines to move the needed building materials both vertically and horizontally. Having all but equaled the span of the Pantheon in stone, Brunelleschi was hailed as the man who ?renewed Roman masonry work?; the dome was established as the paragon of built form.

The next great dome of the Renaissance was that of St. Peter's Basilica in Rome, begun by Pope Julius II in 1506. The technology was very similar to that of Brunelleschi, and the diameter is nearly the same. The dome's design went through many changes and extended over a period of nearly 80 years. The major contributors to the design were the painter and sculptor Michelangelo, who served as architect from 1546 to 1564, and the architects Giacomo della Porta and Domenico Fontana, under whose direction it was finally built during the 1580s. The dome was considerably thinner than that of Florence and was reinforced by three tie rings made of continuous iron chains. It developed numerous cracks, and in the 1740s five more chains were added to further stabilize it. Since the dome used a proven technology, most of the design was done on paper with drawings.

Another large dome of this period was that of St. Paul's Cathedral in London, which was built from 1675 to 1710 by the English architect Sir Christopher Wren. In the early stages of the design process only two physical models were used; later efforts included extensive drawings and apparently also mathematical modeling with numerical calculations. Wren had begun his career as a mathematician and physical scientist and was professor of astronomy at Oxford from 1661 to 1673 before becoming a full-time architect. With this background he was thus able to profit from the first theoretical determination of the catenary curve as the most efficient profile of the arch and dome, which was published by the Scottish mathematician David Gregory in 1697. Wren's solution to the dome, which has a diameter of 34.5 metres (113 feet), was a series of three nested shells, of which the middle one is the true structure. This middle dome is built of brick in a nearly conical catenary form, owing to the large concentrated load of the lantern on top, and constrained by iron chains; it supports a triangularly braced timber framework to which is attached the exterior surfacing of lead sheets. Within the middle dome is a shallower catenary dome that carries only its own weight and serves as a ceiling for the interior space. Wren's concealed structure, to which were applied the desired internal and external forms, has become a standard architectural technique.

Revival of Roman technics and materials

In addition to Roman forms in masonry, the Renaissance recovered other Roman technologies, including timber trusses. Giorgio Vasari used king-post timber trusses for a 20-metre (66-foot) span in the roof of the Uffizi, or municipal office building, in Florence in the mid-16th century. At the same time, the Venetian architect Andrea Palladio used a fully triangulated timber truss for a bridge with a span of 30.5 metres (100 feet) over the Cimone River. Palladio clearly understood the importance of the carefully detailed diagonal members, for in his diagram of the truss in his Four Books on Architecture he said that they ?support the whole work.? The tension connections of the timber members in the truss were joined with iron cramps and bolts.

Trussed spans in the range of 20?26 metres (65?85 feet) became fairly common in building roofs. In 1664 Wren used timber trusses with a span of about 22 metres (73 feet) in the roof of the Sheldonian Theatre at Oxford. But a precise theoretical understanding of the truss, and major use of it in buildings, would not come until the 19th century.

Another Roman material that was revived and much improved in the Renaissance was clear glass. A new technique for making it was perfected in Venice in the 16th century. It was known as the crown glass method and was originally used for making dinner plates. Glassblowers spun the molten glass into flat disks up to a metre in diameter; the disks were polished after they had cooled and were cut into rectangular shapes. The first record of crown glass windows is their installation in double-hung counterweighted sliding-sash frames, at Inigo Jones's Banqueting House in London in 1685. Large areas of such glass became common in the 1700s, pointing the way toward the great glass and iron buildings of the 19th century.

The efficiency of interior heating was improved by the introduction of cast-iron and clay-tile stoves, which were placed in a free-standing position in the room. The radiant heat they produced was uniformly distributed in the space, and they lent themselves to the burning of coal?a new fuel that was rapidly replacing wood in western Europe. When European builders had recovered the technology of the classical world in brick, stone, and timber, a stable plateau was reached in the development of the building arts; these materials and technics were well suited to the churches, palaces, and fortifications that their patrons required. The Industrial Revolution, however, brought new materials and the demand for new building types that completely transformed building technology.

The first industrial age

Development of iron technology

The last half of the 18th century saw the unfolding of a series of events, primarily in England, that later historians would call the first Industrial Revolution, which would have a profound influence on society as a whole as well as on building technology. Among the first of these events was the large-scale production of iron, beginning with the work of Abraham Darby, who in 1709 was the first to use coke as a fuel in the smelting process. The ready availability of iron contributed to the development of machinery, notably James Watt's double-acting steam engine of 1769. Henry Cort developed the puddling process for making wrought iron in 1784, and in the same year he built the first rolling mill, powered by a steam engine, to produce rolled lengths of wrought-iron bars, angles, and other shapes. Cast iron, which has a higher carbon content than wrought iron but is more brittle, was also produced on a large scale. Standard iron building elements soon appeared, pointing the way to the development of metal buildings.

Early applications of iron in construction are found several centuries prior to the industrial age. There are records of iron chain suspension bridges with timber decks in China from the early Ming dynasty (1368?1644); some of them, such as the Liu-Tung Bridge?the object of a famous battle on Mao Zedong's (Mao Tse-tung's) Long March in 1935?have survived in a much-restored condition. The iron tension chains in the domes of St. Peter's and St. Paul's cathedrals are other examples. But the first large cast-iron structure of the industrial age was the bridge over the River Severn at Ironbridge. Built by the iron founder Abraham Darby III between 1777 and 1779, it has a span of 30 metres (100 feet), using five circular-form arches that are reduced to a spidery web of slender iron ribs. Each arch was cast in two pieces with a maximum dimension of 21 metres (70 feet), which were difficult to move from the foundry to the site and to set in place. Smaller, more easily handled pieces characterized the rapid application of iron to buildings that followed. Solid cast-iron columns were used in St. Anne's Church in Liverpool as early as 1772, and hollow tubular columns of increased efficiency were developed in the 1790s. The first use of wrought-iron trusses, which were made of flat bars riveted together, was in a 28-metre (92-foot) span for the roof of the Théâtre-Français in Paris in 1786 by the architect Victor Louis; there iron was used not so much for its strength as its noncombustibility, which, it was hoped, would reduce the hazard of fire. For the same reason, about 1800 the British textile industry began to use partial metal framing in mill buildings up to seven stories high. Hollow cast-iron cylindrical columns were spaced at about three metres (10 feet) on centre and supported cast-iron tee beams spanning up to 4.5 metres (15 feet); the floors were bridged by brick arches resting on the bottom flanges of the tee beams; at the perimeter the beams rested on masonry bearing walls, which gave the structure its lateral stability. This prototype of the iron-frame building with exterior masonry walls soon set a standard that would continue to the end of the century.

The completely independent iron frame without masonry adjuncts emerged slowly in a series of special building types. The first modest example was Hungerford Fish Market (1835) in London. Timber was forbidden because of sanitation requirements; the cast-iron beams spanned 9.7 metres (32 feet) with three-metre (10-foot) cantilevers on either side, and the hollow cast-iron columns also served as roof drains. All lateral stability was provided by the rigid joints between columns and beams. The next type to use the full iron frame was the greenhouse, which provided a controlled luminous and thermal environment for exotic tropical plants in the cold climate of northern Europe. Among the first of these was the Palm House at Kew Gardens near London; it was built by the architect Decimus Burton in the 1840s.

A spectacular series of iron and glass buildings for conservatories and exhibition halls continued to the end of the century. The most important of these was the Crystal Palace, built in London's Hyde Park to house the Great Exhibition of 1851. This vast building, 564 metres (1,851 feet) long, was built entirely of standardized parts. Cast-iron columns carried iron trusses of three different spans?7.3 metres (24 feet), 14.6 metres (48 feet), and 21.9 metres (72 feet)?in riveted wrought iron; spanning between the trusses were ingenious ?Paxton gutters? made of wooden compression members above iron tension rods that prestressed the wood to reduce deflection. All these prefabricated elements were simply bolted or clipped together on the site to enclose a space of 90,000 square metres (1,000,000 square feet) in only six months. But the major triumph of the Crystal Palace was its all-glass enclosure, made of standard panes 25 ´ 124 centimetres (10 ´ 49 inches) in size; the huge space was flooded with light that was scarcely interrupted by the diaphanous metal framing?it resembled a great secular cathedral realizing the ultimate ambition of the medieval masons.

The French also produced a number of fine iron and glass exhibition halls, including one with a 48-metre (160-foot) span in 1855. Others with somewhat smaller spans, but larger enclosed areas than the Crystal Palace, followed in 1867 and 1878. Iron trusses with glazed roofs were also used in the train sheds of railway stations that were built throughout western Europe. The New Street Station in Birmingham, Eng. (1854), had a train shed with an iron truss roof spanning 64 metres (211 feet). It was apparently the first building to exceed the span of the Pantheon. One of the largest was St. Pancras Station (1873) in London, which featured a glazed hall spanned by 74-metre (243-foot) trussed iron arches. After the brilliant successes of midcentury, iron and glass construction was applied in a more prosaic series of buildings that continued to be built until 1900.

Manufactured building materials

The production of brick was industrialized in the 19th century. The laborious process of hand-molding, which had been used for 3,000 years, was superseded by

?pressed? bricks. These were mass-produced by a mechanical extrusion process in which clay was squeezed through a rectangular die as a continuous column and sliced to size by a wire cutter. There was also a proliferation of elaborately shaped and stamped masonry units. Periodically fired beehive kilns (stoked by coke) continued to be used, but the continuous tunnel kiln, through which bricks were moved slowly on a conveyor belt, had appeared by the end of the century. The new methods considerably reduced the cost of brick, and it became one of the constituent building materials of the age.

Timber technology underwent rapid development in the 19th century in North America, where there were large forests of softwood fir and pine trees that could be harvested and processed by industrial methods; steam- and water-powered sawmills began producing standard-dimension timbers in quantity in the 1820s. The production of cheap machine-made nails in the 1830s provided the other necessary ingredient that made possible a major innovation in building construction, the balloon frame; the first example is thought to be a warehouse erected in Chicago in 1832 by George W. Snow. There was a great demand for small buildings of all types as the North American continent was settled, and the light timber frame provided a quick, flexible, and inexpensive solution to this problem. In the balloon frame system, traditional heavy timbers and complex joinery were abandoned. The building walls were framed with 5 ´ 10-centimetre (2 ´ 4-inch) vertical members, or studs, placed at 40 centimetres (16 inches) on centre (that is, measured between the centre points of each); these in turn supported the roof and floor joists, usually 5 ´ 25 centimetres (2 ´ 10 inches) also placed 40 centimetres (16 inches) apart and capable of spanning up to six metres (20 feet). Lateral stability was achieved by light diagonal braces let into the studs or, more commonly, by two-centimetre (0.75-inch) thick diagonal boards applied to all exterior walls and to floor and roof joists, creating a rigid, light box. Openings were cut through the framing and sheathing as required. All connections were made with machine-made nails, which were easily driven through the soft, thin timbers. A wide variety of interior and exterior surfacing materials could be applied to the frame, including timber siding, stucco, and brick veneer. The balloon frame building, made with manufactured materials and requiring only a few hand tools and little skill to build, has remained a popular and inexpensive form of construction to the present day.

Building science

A significant achievement of the first industrial age was the emergence of building science, particularly the elastic theory of structures. With it, mathematical models could be used to predict structural performance with considerable accuracy, provided there was adequate quality control of the materials used. Although some elements of the elastic theory, such as the Swiss mathematician Leonhard Euler's theory of column buckling (1757), were worked out earlier, the real development began with the English scientist Thomas Young's modern definition of the modulus of elasticity in 1807. Louis Navier published the elastic theory of beams in 1826, and three methods of analyzing forces in trusses were devised by Squire Whipple, A. Ritter, and James Clerk Maxwell between 1847 and 1864. The concept of a statically determinate structure?that is, a structure whose forces could be determined from Newton's laws of motion alone?was set forth by Otto Mohr in 1874, after having been used intuitively for perhaps 40 years. Most 19th-century structures were purposely designed and fabricated with pin joints to be statically determinate; it was not until the 20th century that statically indeterminate structures became readily solvable. The elastic theory formed the basis of structural analysis until World War II, when bomb-damaged buildings were observed to behave in unpredicted ways and the underlying assumptions of the theory were found to require modification.

Emergence of design professionals

The coming of the industrial age also marked a major change in the role of the architect. The artist-architects of the Renaissance had the twin patrons of church and state upon whom they could depend for commissions. In the rising industrial democracies the market for large-scale buildings worthy of an architect's attention widened, and the different users asked for a bewildering range of new building types. The response of the architect was to develop the new role of licensed professional on the model of professions such as law and medicine. In addition, with the coming of building science, there was a further division of labour in the design process; structural engineering appeared as a separate discipline specializing in the application of mathematical models in building. One of the first buildings for which the architect and engineer were separate persons was the Granary (1811) in Paris. Societies representing the building design professions were founded, including the Institution of Civil Engineers (1818) and the Royal Institute of British Architects (1834), both in London, and the American Institute of Architects (1857). Official government licensing of architects and engineers, a goal of these societies, was not realized until much later, beginning with the Illinois Architects Act of 1897. Concurrent with the rise of professionalism was the development of government regulation, which took the form of detailed municipal and national building codes specifying both prescriptive and performance requirements for buildings.

Improvements in building services

Environmental control technologies began to develop dramatically in the first industrial age. The first major advance was the use of coal gas for lighting. Coal gas was first made in the 1690s by heating coal in the presence of water to yield methane, and in 1792 William Murdock developed the gas jet lighting fixture. The first large building to have gas lighting (from a small gas plant on the site) was James Watt's foundry in Birmingham in 1803. The Gas Light and Coke Company was founded in London in 1812 as the first real public utility, producing coal gas as a part of the coking process in large central plants and distributing it through underground pipes to individual users; soon many major cities had gasworks and distribution networks. Gas was expensive, however, and was used mainly for lighting, not for heating or cooking; it also contained many impurities that produced undesirable products of combustion (particularly carbon soot) in occupied spaces. Relatively pure methane in the form of natural gas would not be available until the exploitation of large oil fields in the 20th century.

The stove and fireplace continued as the major sources of space heating throughout this period, but the development of the steam engine and its associated boilers led to a new technology in the form of steam heating. James Watt heated his own office with steam running through pipes as early as 1784. During the 19th century, systems of steam and later hot-water heating were gradually developed; these used coal-fired central boilers connected to networks of pipes that distributed the heated fluid to cast-iron radiators and returned it to the boiler for reheating. Steam heat was a major improvement over stoves and fireplaces because all combustion products were eliminated from occupied spaces, but heat sources were still localized at the radiators.

Plumbing and sanitation systems in buildings advanced rapidly in this period. Public water-distribution systems were the essential element; the first large-scale example of a mechanically pressurized water-supply system was the great array of waterwheels installed by Louis XIV at Marley on the Marne River in France to pump water for the fountains at Versailles, about 18 kilometres (10 miles) away. The widespread use of cast-iron pipes in the late 18th century made higher pressures possible, and they were used by Napoleon in the first steam-powered municipal water supply for a section of Paris in 1812. Gravity-powered underground drainage systems were installed along with water-distribution networks in most large cities of the industrial world during the 19th century; sewage-treatment plants were introduced in the 1860s. Permanent plumbing fixtures appeared in buildings with water supply and drainage, replacing portable basins, buckets, and chamber pots. Joseph Bramah invented the metal valve-type water closet as early as 1778, and other early lavatories, sinks, and bathtubs were of metal also; lead, copper, and zinc were all tried. The metal fixtures proved difficult to clean, however, and in England during the 1870s Thomas Twyford developed the first large one-piece ceramic lavatories as well as the ceramic washdown water closet. At first these ceramic fixtures were very expensive, but their prices declined until they became standard, and their forms remain largely unchanged today. The bathtub proved to be too large for brittle ceramic construction, and the porcelain-enamel cast-iron tub was devised about 1870; the double-shell built-in type still common today appeared about 1915.

The second industrial age

Introduction of steel building technology

If the first industrial age was one of iron and steam, the second industrial age, which began in about 1880, could be called one of steel and electricity. Mass production of this new material and of this new form of energy also transformed building technology. Steel was first made in large quantities for railroad rails. Rolling of steel rails (which was adapted from wrought-iron rolling technology) and other shapes such as angles and channels began about 1870; it made a much tougher, less brittle metal. Steel was chosen as the principal building material for two structures built for the Paris Exposition of 1889: the Eiffel Tower and the Gallery of Machines. Gustave Eiffel's tower was 300 metres (1,000 feet) high, and its familiar parabolic curved form has become a symbol of Paris itself; its height was not exceeded until 1929. The Gallery of Machines was designed by the architect C.-L.-F. Dutert and the engineer Victor Contamin with great three-hinged arches spanning 114 metres (380 feet) and extending more than 420 metres (1,400 feet). Its glass-enclosed clear span area of 48,727 square metres (536,000 square feet) has never been equaled; in fact, it was so large that no regular use for it could be found after the exposition closed, and this magnificent building was demolished in 1910.

Early steel-frame high-rises

While these prodigious structures were the centre of attention, a new and more significant technology was developing: the steel-framed high-rise building. It began in Chicago, a city whose central business district was growing rapidly. The pressure of land values in the early 1880s led owners to demand taller buildings. The architect-engineer William Le Baron Jenney responded to this challenge with the 10-story Home Insurance Company Building (1885), which had a nearly completely all-metal structure. The frame consisted of cast-iron columns supporting wrought-iron beams, together with two floors of rolled-steel beams that were substituted during construction; this was the first large-scale use of steel in a building. The metal framing was completely encased in brick or clay-tile cladding for fire protection, since iron and steel begin to lose strength if they are heated above about 400˚ C (750˚ F). Jenney's Manhattan Building (1891) had the first vertical truss bracing to resist wind forces; rigid frame or portal wind bracing was first used in the neighbouring Old Colony Building (1893) by the architects William Holabird and Martin Roche. The all-steel frame finally appeared in Jenney's Ludington Building (1891) and the Fair Store (1892).

The foundations of these high-rise buildings posed a major problem, given the soft clay soil of central Chicago. Traditional spread footings, which dated back to the Egyptians, proved to be inadequate to resist settlement due to the heavy loads of the many floors, and timber piles (a Roman invention) were driven down to bedrock. For the 13-story Stock Exchange Building (1892), the engineer Dankmar Adler employed the caisson foundation used in bridge construction. A cylindrical shaft braced with board sheathing was hand-dug to bedrock and filled with concrete to create a solid pier to receive the heavy loads of the steel columns.

By 1895 a mature high-rise building technology had been developed: the frame of rolled steel I beams with bolted or riveted connections, diagonal or portal wind bracing, clay-tile fireproofing, and caisson foundations. The electric-powered elevator provided vertical transportation, but other environmental technologies were still fairly simple. Interior lighting was still largely from daylight, although supplemented by electric light. There was steam heating but no cooling, and ventilation was dependent on operating windows; thus these buildings needed narrow floor spaces to give adequate access to light and air. Of equal importance in high-rise construction was the introduction of the internal-combustion engine (which had been invented by Nikolaus Otto in 1876) at the building site; it replaced the horse and human muscle power for the heaviest tasks of lifting. Over the next 35 years, higher steel-frame buildings were built; in Chicago the Masonic Temple (1892) of Daniel Burnham and John Root reached 22 stories (91 metres or 302 feet), but then the leadership shifted to New York City with the 26-story Manhattan Life Building (1894). The Singer Building (1907) by the architect Ernest Flagg rose to 47 stories (184 metres or 612 feet), Cass Gilbert's Woolworth Building (1913) attained a height of 238 metres (792 feet) at 55 stories, and Shreve, Lamb & Harmon's 102-story Empire State Building (1931) touched 381 metres (1,250 feet). The race for higher buildings came to an abrupt halt with the Great Depression and World War II, and high-rise construction was not resumed until the late 1940s.

Steel long-span construction

Long-span structures in steel developed more slowly than the high-rise in the years from 1895 to 1945, and none exceeded the span of the Gallery of Machines. Two-hinge (made of a single member hinged at each end) and three-hinge (made of two members hinged at each end and at the meeting point at the crown) trussed arches were widely used, the largest examples being two great airship hangars for the U.S. Navy in New Jersey?the first built in 1922 with a span of 79 metres (262 feet), the second in 1942 with a span of 100 metres (328 feet). The flat truss was used also, reaching a maximum span of 91 metres (300 feet) in the Glenn L. Martin Co. Aircraft Assembly Building (1937) in Baltimore. Electric arc welding, another important steel technology, was applied to building construction at this time, although the principle had been developed in the 1880s. The first all-welded multistory buildings were a series of factories for the Westinghouse Company, beginning in 1920. The welded rigid frame became a new structural type for medium spans, reaching a length of 23 metres (77 feet) in the Cincinnati Union Terminal (1932), but widespread use of welding did not come until after 1945.

Reintroduction of concrete

The second industrial age also saw the reemergence of concrete in a new composite relationship with steel, creating a technology that would rapidly assume a major role in building construction. The first step in this process was the creation of higher-strength artificial cements. Lime mortar?made of lime, sand, and water?had been known since ancient times. It was improved in the late 18th century by the British engineer John Smeaton, who added powdered brick to the mix and made the first modern concrete by adding pebbles as coarse aggregate. Joseph Aspdin patented the first true artificial cement, which he called Portland Cement, in 1824; the name implied that it was of the same high quality as Portland stone. To make portland cement, Aspdin burned limestone and clay together in a kiln; the clay provided silicon compounds, which when combined with water formed stronger bonds than the calcium compounds of limestone. In the 1830s Charles Johnson, another British cement manufacturer, saw the importance of high-temperature burning of the clay and limestone to a white heat, at which point they begin to fuse. In this period, plain concrete was used for walls, and it sometimes replaced brick in floor arches that spanned between wrought-iron beams in iron-framed factories. Precast concrete blocks also were manufactured, although they did not effectively compete with brick until the 20th century.

The invention of reinforced concrete

The first use of iron-reinforced concrete was by the French builder François Coignet in Paris in the 1850s. Coignet's own all-concrete house in Paris (1862), the roofs and floors reinforced with small wrought-iron I beams, still stands. But reinforced concrete development began with the French gardener Joseph Monier's 1867 patent for large concrete flowerpots reinforced with a cage of iron wires. The French builder François Hennebique applied Monier's ideas to floors, using iron rods to reinforce concrete beams and slabs; Hennebique was the first to realize that the rods had to be bent upward to take negative moment near supports. In 1892 he closed his construction business and became a consulting engineer, building many structures with concrete frames composed of columns, beams, and slabs. In the United States Ernest Ransome paralleled Hennebique's work, constructing factory buildings in concrete. High-rise structures in concrete followed the paradigm of the steel frame. Examples include the 16-story Ingalls Building (1903) in Cincinnati, which was 54 metres (180 feet) tall, and the 11-story Royal Liver Building (1909), built in Liverpool by Hennebique's English representative, Louis Mouchel. The latter structure was Europe's first skyscraper, its clock tower reaching a height of 95 metres (316 feet). Attainment of height in concrete buildings progressed slowly owing to the much lower strength and stiffness of concrete as compared with steel.

Between 1900 and 1910 the elastic theory of structures was at last applied to reinforced concrete in a scientific way. Emil Morsch, the chief engineer of the German firm of Wayss and Freitag, formulated the theory, which was verified by detailed experimental testing at the Technical University of Stuttgart. These tests established the need for deformed bars for good bonding with concrete and demonstrated that the amount of steel in any member should be limited to about 8 percent of the area; this assures the slow elastic failure of the steel, as opposed to the abrupt brittle failure of the concrete, in case of accidental overloading. In 1930 the American engineer Hardy Cross introduced relaxation methods for the approximate analysis of rigid frames, which greatly simplified the design of concrete structures. In the Johnson-Bovey Building (1905) in Minneapolis, the American engineer C.A.P. Turner employed concrete floor slabs without beams (called flat slabs or flat plates) that used diagonal and orthogonal patterns of reinforcing bars. The system still used today?which divides the bays between columns into column strips and middle strips and uses only an orthogonal arrangement of bars?was devised in 1912 by the Swiss engineer Robert Maillart.

The concrete dome

Concrete was also applied to long-span buildings, an early example being the Centennial Hall (1913) at Breslau, Ger. (now Wroclaw, Pol.), by the architect Max Berg and the engineers Dyckerhoff & Widmann; its ribbed dome spanned 65 metres (216 feet), exceeding the span of the Pantheon. More spectacular were the great airship hangars at Orly constructed by the French engineer Eugène Freyssinet in 1916; they were made with nine-centimetre- (3.5-inch-) thick corrugated parabolic vaults spanning 80 metres (266 feet) and pierced by windows. In the 1920s Freyssinet made a major contribution to concrete technology with the introduction of pretensioning. In this process, the reinforcing wires were stretched in tension, and the concrete was poured around them; when the concrete hardened, the wires were released, and the member acquired an upward deflection and was entirely in compression. When the service load was applied, the member deflected downward to a flat position, remaining entirely in compression, and it did not develop the tension cracks that plague ordinary reinforced concrete. Widespread application of pretensioning was not made until after 1945.

Shell construction in concrete also began in the 1920s; the first example was a very thin (6 centimetres) hemispherical shell for a planetarium (1924) in Jena, Ger., spanning 25 metres (82 feet). In 1927 an octagonal ribbed shell dome with a span of 66 metres (220 feet) was built to house a market hall in Leipzig. Many variations of thin shells were devised for use in industrial buildings. The shell emerged as a major form of long-span concrete structure after World War II.

Development of building service and support systems

Vertical transportation

Elisha Graves Otis developed the first safe steam-powered roped elevators with toothed guide rails and catches in the late 1850s. The steam-powered hydraulic elevator, which was limited to buildings of about 15 stories, was developed in 1867 by the French engineer Léon Édoux. The development of the electric motor by George Westinghouse in 1887 made possible the invention of the high-speed electric-powered roped elevator (called ?lightning? elevators in comparison to the slower hydraulics) in 1889 and the electric-powered moving staircase, or escalator, in the 1890s.

Lighting

In the second industrial age, environmental technologies developed rapidly. Most of these technologies involved the use of electric power, which declined in cost during this period. The carbon-arc electric light was demonstrated as early as 1808, and the British physicist Michael Faraday devised the first steam-powered electric generator to operate a large carbon-arc lamp for the Foreland Lighthouse in 1858. But the carbon-arc lamp was so bright and required so much power that it was never widely used and was rapidly superseded by the simultaneous invention of the carbon-filament bulb by Thomas Edison and Joseph Swan in 1879. The carbon-filament bulb was highly inefficient, but it banished the soot and fire hazards of coal-gas jets and soon gained wide acceptance. It was succeeded by the more efficient tungsten-filament incandescent bulb, developed by George Coolidge of the General Electric Company, which first appeared in 1908; the double-coiled filament used today was introduced about 1930.

Edison experimented with gas-discharge light tubes in 1896, and Georges Claude in France and Moore in England produced the first practical discharge tubes using noble gases such as neon and argon; these tubes were first used to outline the facade of the West End Cinema in London in 1913 and were rapidly exploited for signs and other decorative purposes. In 1938 General Electric and Westinghouse produced the first commercial fluorescent discharge lamps using mercury vapour and phosphor-coated tubes to enhance visible light output. Fluorescent tubes had roughly double the efficiency of tungsten lamps and were rapidly adopted for commercial and office use. Light intensity increased in all buildings as electric costs decreased, reaching a peak in about 1970.

Gaseous-discharge lamps using high-pressure mercury and sodium vapour were developed in the 1960s but found only limited application in buildings; they are of such high intensity and marked colour that they are used mostly in high-ceilinged spaces and for exterior lighting.

Heating and cooling systems

Steam and hot-water heating systems of the late 19th century provided a reasonable means for winter heating, but no practical methods existed for artificial cooling, ventilating, or humidity control. In the forced-air system of heating, air replaced steam or water as the fluid medium of heat transfer, but this was dependent on the development of powered fans to move the air. Although large, crude fans for industrial applications in the ventilation of ships and mines had appeared by the 1860s, and the Johns Hopkins Hospital in Baltimore had a successful steam-powered forced-air system installed in 1873, the widespread application of this system to buildings only followed the development of electric-powered fans in the 1890s.

Important innovations in cooling technology followed. The development of refrigeration machines for food storage played a role, but the key element was Willis Carrier's 1906 patent that solved the problem of humidity removal by condensing the water vapour on droplets of cold water sprayed into an airstream. Starting with humidity control in tobacco and textile factories, Carrier slowly developed his system of ?man-made weather,? finally applying it together with heating, cooling, and control devices as a complete system in Graumann's Metropolitan Theater, Los Angeles, in 1922. The first office building air-conditioned by Carrier was the 21-story Milam Building (1928) in San Antonio, Texas. It had a central refrigeration plant in the basement that supplied cold water to small air-handling units on every other floor; these supplied conditioned air to each office space through ducts in the ceiling; the air was returned through grills in doors to the corridors and then back to the air-handling units. A somewhat different system was adopted by Carrier for the 32-story Philadelphia Savings Fund Society Building (1932). The central air-handling units were placed with the refrigeration plant on the 20th floor, and conditioned air was distributed through vertical ducts to the occupied floors and horizontally to each room and returned through the corridors to vertical exhaust ducts that carried it back to the central plant. Both systems of air handling, local and central, are still used in high-rise buildings. The Great Depression and World War II reduced the demand for air-conditioning systems, and it was not until the building of the United Nations Secretariat in New York City in 1949 that Carrier produced a method of air conditioning that could deal effectively with the large heat loads imposed by the building's all-glass curtain walls. The conditioned air was delivered not only from the ceiling but also through pipe coil convector units just inside the glass wall. The pipe coil convectors contained centrally supplied warm or cold water to further temper the heat loss or gain at the perimeter; conditioned air and water were centrally supplied from four mechanical floors spaced within the building's 39-story height.

Carrier's ?Weathermaster? system was energy-intensive, appropriate to the declining energy costs of the time, and it was adopted for most of the all-glass skyscrapers that followed in the next 25 years. In the 1960s the so-called dual-duct system appeared; both warm and cold air were centrally supplied to every part of the building and combined in mixing boxes to provide the appropriate atmosphere. The dual-duct system also consumed much energy, and, when energy prices began to rise in the 1970s, both it and the Weathermaster system were supplanted by the variable air volume (VAV) system, which supplies conditioned air at a single temperature, the volume varying according to the heat loss or gain in the occupied spaces. The VAV system requires much less energy and is widely used.

In the early 1950s, air-conditioning systems were reduced to very small electric-powered units capable of cooling single rooms. These were usually mounted in windows to take in fresh air and to remove heat to the atmosphere. These units found widespread application in the retrofitting of existing buildings?particularly houses and apartment buildings?and have since found considerable application in new residential buildings.

The relatively high energy costs of the 1970s also prompted interest in various forms of solar heating, both for interior spaces and for domestic hot water, but, except for residential passive solar heating, the relative decline in energy prices in the 1980s made such systems unattractive.

The study of thermodynamics in the late 19th century included the heat-transfer properties of materials and led to the concept of thermal insulation?that is, a material that has a relatively low rate of heat transfer. As building atmospheres became more carefully controlled after 1900, more attention was given to the thermal insulation of building enclosures (envelopes). One of the best insulators is air, and materials that trap air in small units have low heat-transfer rates; wool and foam are excellent examples. The first commercial insulations, in the 1920s, were mineral wools and vegetable-fibreboards; fibreglass wool appeared in 1938. Foam glass, the first rigid insulating foam, was marketed in the 1930s, and after 1945 a wide variety of plastic foam insulations was developed. Since the 1970s most building codes have set minimum requirements for insulation of building envelopes, and these have proved to be very cost-effective in saving energy.

Glass as a building material

Glass underwent considerable development in the second industrial age. The making of clear plate glass was perfected in the late 19th century, as were techniques of sandblasting and etching it. In the United States in 1905 the Libbey Owens Glass Company began making sheet glass by a continuous drawing process from a reservoir of molten glass; its surface was somewhat distorted, but it was much cheaper than plate glass. Prefabricated panels of double glazing about 2.5 centimetres (one inch) thick were first made in the 1940s, although the insulating principle of air trapped between two layers of glass had been recognized much earlier. Hollow glass blocks were introduced by the Corning Company in 1935. In 1952 the Pilkington Brothers in England developed the float glass process, in which a continuous 3.4-metre- (11-foot-) wide ribbon of glass floated over molten tin and both sides were fire finished, avoiding all polishing and grinding; this became the standard method of production. Pilkington also pioneered the development of structural glass mullions in the 1960s. In the 1950s the rise of air conditioning led to the marketing of tinted glass that would absorb and reduce solar gain, and in the 1960s reflective glass with thin metallic coatings applied by the vacuum plating process was introduced, also to reduce solar gain. Heat-mirror glass, which has a transparent coating that admits the short-wavelength radiation from the sun but tends to reflect the longer-wavelength radiation from within occupied spaces, was introduced in 1984; when combined with double glazing, its insulating value approaches that of a wall.

High-rise construction since 1945

Use of steel and other metals

The second great age of high-rise buildings began after the end of World War II, when the world economy and population again expanded. It was an optimistic time with declining energy costs, and architects embraced the concept of the tall building as a glass prism. This idea had been put forward by the architects Le Corbusier and Ludwig Mies van der Rohe in their visionary projects of the 1920s. These designs employed the glass curtain wall, a non-load-bearing ?skin? attached to the exterior structural components of the building. The earliest all-glass curtain wall, which was only on a single street facade, was that of the Hallidie Building (1918) in San Francisco. The first multistory structure with a full glass curtain wall was the A.O. Smith Research Building (1928) in Milwaukee by Holabird and Root; in it the glass was held by aluminum frames, an early use of this metal in buildings. But these were rare examples, and it was not until the development of air conditioning, fluorescent lighting, and synthetic rubber sealants after 1945 that the glass prism could be realized.

The paradigm of the glass tower was defined by the United Nations Secretariat Building (1949) in New York City; Wallace Harrison was the executive architect, but Le Corbusier also played a major role in the design. The UN building, which featured a Weathermaster air-conditioning system and green-tinted glass walls, helped set the standard for tall buildings around the world. Several other influential buildings?such as Mies van der Rohe's 26-story 860?880 Lake Shore Drive Apartments (1951) in Chicago and Skidmore, Owings & Merrill's 21-story Lever House (1952) in New York City?helped to further establish the technology of curtain walls. Perhaps the most important element was the development of extruded-aluminum mullion and muntin shapes to support the glass. Aluminum began to be produced in quantity in the United States by the Hall process in 1886; this process for separating the metal from the ore required large amounts of electricity, and declining energy costs after World War II influenced the development of this building technology. Aluminum forms a coating of transparent oxide that protects it against corrosion; this oxide layer can be artificially thickened and coloured through a process called anodizing. Anodized aluminum was first used in the windows of the Cambridge University Library in England in 1934. Aluminum became the principal material of curtain-wall framing because of its corrosion resistance and ease of forming by means of the extrusion process, in which the metal is forced through a series of dies to create complex cross-sectional shapes. Formed sheet aluminum is also used for opaque curtain-wall panels. Other metals used in curtain walls are stainless steel (a compound of 82 percent iron and 18 percent chromium) and so-called weathering steel, copper-bearing steel alloys that form an adherent oxide layer. The bronze curtain wall of Mies van der Rohe's Seagram Building (1954?58) in New York City proved to be an isolated example. Probably of equal importance in curtain-wall construction was the development of cold-setting rubbers during World War II; these form the elastic sealants that successfully seal the joints between glass and metal and between metal and metal against wind and rain. In the late 1970s the development of artificial diamonds made possible cutting tools that slice stone wafer-thin, and it became an important component of curtain walls.

Following the development of the curtain wall, new forms of structure appeared in high-rise buildings. As environmental control systems increased in cost, economic pressures worked to produce more efficient structures. In 1961 the 60-story Chase Manhattan Bank Building, designed by Skidmore, Owings & Merrill, had a standard steel frame with rigid portal wind bracing, which required 275 kilograms of steel per square metre (55 pounds of steel per square foot), nearly the same as the Empire State Building of 30 years earlier. Economy of structure in tall buildings was demonstrated by the same firm only nine years later in the John Hancock Building in Chicago. It used a system of exterior diagonal bracing to form a rigid tube devised by the engineer Fazlur Khan; although the Hancock building is 100 stories, or 343 metres (1,127 feet), high, its structure is so efficient that it required only 145 kilograms of steel per square metre (29 pounds per square foot). The framed tube, which Khan developed for concrete structures, was applied to other tall steel buildings. Khan used a steel system of nine bundled tubes of different heights?each 22.5 metres (75 feet) square with columns spaced at 4.5 metres (15 feet)?to form the structure of the 110-story, 442-metre (1,450-foot) Sears Tower (1973), also in Chicago. (See Researcher's Note: Height of the Sears Tower.) Considerably taller buildings are possible with current technology, but their erection also depends on general economic considerations and the resulting marketability of floor space.

Use of reinforced concrete

Parallel to the development of tall steel structures, substantial advancements in high-rise structural systems of reinforced concrete have been made since 1945. The first of these was the introduction of the shear wall as a means of stiffening concrete frames against lateral deflection, such as results from wind or earthquake loads; the shear wall acts as a narrow deep cantilever beam to resist lateral forces. In 1958 the architect Milton Schwartz and engineer Henry Miller used shear walls to build the 39-story Executive House in Chicago to a height of 111 metres (371 feet). Of equal importance was the introduction of the perimeter-framed tube form in concrete by Fazlur Khan in the DeWitt?Chestnut Apartments (1963) in Chicago; the building rises 43 stories (116 metres, or 387 feet). Lateral stability was achieved by closely spaced columns placed around the building perimeter and connected together by deep beams. The next step in concrete high-rise construction was the combination of the perimeter-framed tube with a largely solid-walled interior tube or shear walls to give further lateral stability. This was employed by Eero Saarinen and Kevin

Roche in the 35-story CBS Building (1964) in New York City, and the system was further developed by Khan in the 221-metre (725-foot) Shell Oil Building (1967) in Houston. Another new structural form in concrete was introduced by Khan in the 174-metre (570-foot) 780 Third Avenue Office Building (1983) in New York City. This is a framed tube with diagonal bracing achieved by filling in diagonal rows of window openings to create exterior bracing members; this is a very efficient system and may lead to yet taller buildings of this type. Three further innovations helped the rapid rise in height of concrete buildings. One was the development of lightweight concrete, using blast-furnace slag in place of stone as aggregate for floor construction; this reduced the density of the concrete by 25 percent, with a corresponding reduction in the loads the building columns needed to carry. The second was the increase in the ultimate strength of concrete used for columns. Third, the use of pumps to move liquid concrete to the upper floors of tall buildings substantially reduced the cost of placement.

Another important technique developed for concrete high-rise construction is slipforming. In this process, a continuous vertical element of planar or tubular form is continuously cast using a short section of formwork that is moved upward with the pouring process. Slipforming has been used to build a number of very tall structures in Canada, including several industrial chimneys 366 metres (1,200 feet) high and the world's tallest freestanding structure, the CN Tower in Toronto, which contains an observation deck and a massive television antenna and has a total height of 553 metres (1,815 feet). Concrete has shown itself to be a serious competitor with steel in high-rise structures; it is now used for the great majority of tall residential buildings and for a substantial number of tall office buildings.

Postwar developments in long-span construction

After 1945 the dome and the shell vault continued to be the major forms of long-span structures. One innovation was the geodesic dome, which was devised by the architect and engineer R. Buckminster Fuller in the 1940s; in this form the ribs are placed in a triangular or hexagonal pattern and lie on the geodesic lines, or great circles, of a sphere. A very shallow spherical form with aluminum trussed members was used by Freeman Fox & Partners for the Dome Discovery built in London in 1951. Fuller's own patented forms were used in 1958 to build two large hemispheric domes 115.3 metres (384 feet) in diameter using steel tube members. These are used as workshops for the Union Tank Car Company in Wood River, Ill., and Baton Rouge, La. The largest geodesic dome is the Poliedro de Caracas, in Venezuela, built of aluminum tubes spanning 143 metres (469 feet).

@Astrodome, Houston, Texas, 1965.

Another form of steel trussed dome is the lamella dome, which is made of intersecting arches hinged together at their midpoints to form an interlocking network in a diamond pattern. It was used for the first two examples of the great covered sports stadiums built in the United States since the 1960s: the Harris County Stadium, or Astrodome (see photograph), built in Houston, Texas, in 1962?64 with a span of 196 metres (642 feet) and the 207-metre- (678-foot-) diameter Superdome in New Orleans, La., designed by Sverdrup and Parcel and completed in 1973. The steel truss continued to be used and was extended to three dimensions to form space trusses. The longest span of this type was the Narita Hangar at Tokyo International Airport, which used a tied portal truss to span 190 metres (623 feet) supporting a space-truss roof spanning 90 metres (295 feet).

The concrete dome or shell developed rapidly in the 1950s. The St. Louis Lambert Airport Terminal (1954), designed by Hellmuth, Yamasaki and Leinweber, has a large hall 36.6 metres (120 feet) square, spanned by four intersecting thin-shell concrete barrel vaults supported at the four corners; the thickness of the shell varies from 20 centimetres (eight inches) at the supports to 11.3 centimetres (4.5 inches) at the centre. Another example is the King Dome, in Seattle, Wash., which covers a sports stadium with a thin single shell concrete parabolic dome stiffened with ribs 201 metres (661 feet) in diameter.

New forms of the long-span roof appeared in the 1950s based on the steel cables that had long been used in suspension bridges. One example was the U.S. Pavilion at the 1958 Brussels World's Fair, designed by the architect Edward Durell Stone. It was based on the familiar principle of the bicycle wheel; its roof had a diameter of 100 metres (330 feet), with a steel tension ring at the perimeter from which two layers of radial cables were tightly stretched to a small tension ring in the middle?the double layer of cables gave the roof stability against vertical movement. The Oakland?Alameda County Coliseum (1967), by Skidmore, Owings & Merrill, extended this system to 126 metres (420 feet) in diameter, but only a single layer of cables, stiffened by encasing ribs of concrete, connects the inner and outer rings.

Another system derived from bridge construction is the cable-stayed roof. An early example is the TWA Hangar (1956) at Kansas City, Mo., which shelters large aircraft under a double cantilever roof made of semicylindrical shells that reach out 48 meters (160 feet); deflection is reduced and the shells kept in compression by cables that run down from central shear walls to beams in the valleys between the shells. Another example of the cable-stayed roof is the McCormick Place West Exhibition Hall (1987) in Chicago, by Skidmore, Owings & Merrill. Two rows of large concrete masts rise above the roof, supporting steel trusses that span 72 metres (240 feet) between the masts and cantilever 36 metres (120 feet) to either side; the trusses are also supported by sets of parallel diagonal cables that run back to the masts.

A third form of long-span roof structures in tension are air-supported plastic membranes, which were devised by Walter Bird of Cornell University in the late

1940s and were soon in use for swimming pools, temporary warehouses, and exhibition buildings. The Osaka World's Fair of 1970 included many air-supported structures, the largest of which was the U.S. Pavilion designed by the engineers Geiger Berger Associates; it had an oval plan 138 ´ 79 metres (460 ´ 262 feet), and the inflated domed roof of vinyl-coated fabric was restrained by a diagonally intersecting network of steel cables attached to a concrete compression ring at the perimeter. The system of the Osaka Pavilion was adapted for two large sports stadiums built in the 1980s: the Silverdome at Pontiac, Mich., and the Hubert H. Humphrey Metrodome in Minneapolis. Air-supported structures are perhaps the most cost-effective type of structure for very long spans.

Building construction has settled into a period of relative calm after the explosive innovations of the 19th century. Steel, concrete, and timber have become fairly mature technologies, but there are other materials?such as fibre composites?that may yet play a major role in building.

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Modern building practices

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