PART 1

INTRODUCTION

1

HISTORY AND DEVELOPMENT OF MASONRY TECHNOLOGY

The unwritten record of history is preserved in buildings—in temples, fortresses, sanctuaries, and cities constructed of brick and stone. Early efforts to build permanent shelter were limited to the materials at hand. The trees of a primeval forest, the clay and mud of a river valley, the rocks, caves, and cliffs of a mountain range afforded only primitive opportunity for protection, security, and defense and few examples survive. But the stone and brick of skeletal architectural remains date as far back as the temples of Ur built in 3000 B.C., the early walls of Jericho of 8000 B.C., and the vaulted tombs at Mycenae of the fourteenth century B.C. It was the permanence and durability of the masonry which safeguarded this prehistoric record of achievements, and preserved through centuries of war and natural disaster the traces of human development from cave dweller to city builder. Indeed, the history of civilization is the history of its architecture, and the history of architecture is the history of masonry.

1.1 DEVELOPMENT

Stone is the oldest, most abundant, and perhaps the most important *raw building material* of prehistoric and civilized peoples. Stone formed their defense in walls, towers, and embattlements. They lived in buildings of stone, worshiped in stone temples, and built roads and bridges of stone. Builders began to form and shape stone when tools had been invented that were hard enough to trim and smooth the irregular lumps and broken surfaces. Stone building was then freed from the limitations of monolithic slab structures like those at Stonehenge and progressed through the shaped and fitted blocks of the Egyptians to the intricately carved columns and entablatures of the Greeks and Romans.

Brick is the oldest *manufactured* building material, invented almost 10,000 years ago. Its simplicity, strength, and durability led to extensive use, and gave it a dominant place in history alongside stone.

Rubble stone and mud bricks, as small, easily handled materials, could be stacked and shaped to form enclosures of simple or complex design. Hand-shaped, sun-dried bricks, reinforced with such diverse materials as straw and dung, were so effective that kiln-fired bricks did not appear until the third millennium B.C., long after the art of pottery had demonstrated the effects of high temperatures on clay. Some of the oldest bricks in the world, taken from archaeological digs at the site of ancient Jericho, resemble long loaves of bread with a bold pattern of Neolithic thumbprint impressions on their rounded tops (*see Fig. 1-1*). The use of wooden molds did not replace such hand-forming techniques until the early Bronze Age, around 3000 B.C.

Perhaps the most important innovations in the evolution of architecture were the development of masonry arches and domes. Throughout history, the arch was the primary means of overcoming the span limitations of single blocks of stone or lengths of timber, making it possible to bridge spaces once thought too great. Early forms only approximated true "arching" action and were generally false, corbeled arches. True arches carry their loads in simple compression to each abutment, and as long as the joints are roughly aligned at right angles to the compressive stress, the precise curve of the arch is not critical.

The excavation of ruins in Babylonia exposed a masonry arch believed to have been built around 1400 B.C. Arch construction reached a high level of refinement under the Romans, and later developments were limited primarily to the adaptation of different shapes. Islamic and Gothic arches led to the design of groined vaults, and eventually to the high point of cathedral architecture and masonry construction in the thirteenth century.

Simple dome forms may actually have preceded the true arch because, like the corbeled arch, they could be built with successive horizontal rings of masonry, and required no centering. These domes were seen as circular walls gradually closing in on themselves rather than as rings of vertical arches. Barrel vaults were built as early as the thirteenth century B.C., and could also be constructed without centering if one end of the vault was closed off.

Initial exploitation of the true dome form took place from the mid–first century A.D. to the early second century, under the reigns of Nero and Hadrian. The brick dome of the Pantheon in Rome exerts tremendous outward thrusts counteracted only by the massive brick walls encircling its perimeter. Later refinements included the masonry squinch and pendentive, which were instrumental in the construction of the dome of the Florence Cathedral, and buttressing by means of half domes at the sides, as in the Church of Hagia Sophia in Constantinople.

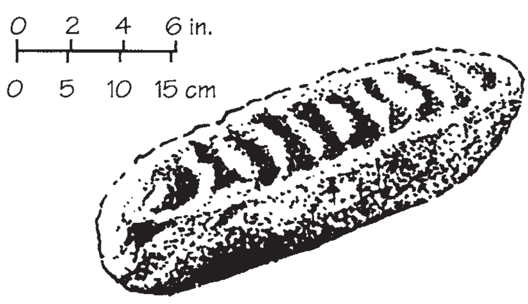


Figure 1-1 Sun-dried brick, circa 8000 B.C.

1.2 DECLINE

Renaissance architecture produced few significant innovations in structural building practices, since designs were based primarily on the classical forms of earlier eras. The forward thrust of structural achievements in masonry essentially died during this period of "enlightenment," and masonry structures remained at an arrested level of development.

With the onslaught of the Industrial Revolution, emphasis shifted to iron, steel, and concrete construction. The invention of portland cement in 1824, refinements in iron production in the early nineteenth century, and the development of the Bessemer furnace in 1854 turned the creative focus of architecture away from masonry.

By the early twentieth century, the demand was for high-rise construction, and the technology of stone and masonry building had not kept pace with the developments of other structural systems. The Chicago School had pioneered the use of iron and steel skeleton frames, and masonry was relegated to secondary usage as facings, in-fill, and fireproofing. The Monadnock Building in Chicago (1891) is generally cited as the last great building in the "ancient tradition" of masonry architecture (*see Fig. 1-2*). Its 16-story *unreinforced* loadbearing walls were required by code to be several feet thick at the base, making it seem unsuited to the demands of a modern industrialized society. Except for the revivalist periods following the 1893 World's Columbian Exposition and the "mercantile classicism" which prevailed for some time, a general shift in technological innovation took place, and skeleton frame construction began to replace loadbearing masonry.

During this period, only Antonio Gaudi's unique Spanish architecture showed innovation in masonry structural design (*see Fig. 1-3*). His "structural rationalism" was based on economy and efficiency of form, using ancient Catalan vaulting techniques, parabolic arches, and inclined piers to bring the supporting masonry under compression. His work also included vaulting with hyperbolic paraboloids and warped "helicoidal" surfaces for greater structural strength. Gaudi, however, was the exception in a world bent on developing lightweight, high-rise building techniques for the twentieth century.

At the time, most considered both concrete and masonry construction to be unsophisticated systems with no tensile strength. Very soon, however, the introduction of iron and steel reinforcement brought concrete a step forward. While concrete technology developed rapidly into complex steel-reinforced systems, masonry research was virtually non-existent, and the widespread application of this new reinforcing technique to masonry never occurred.

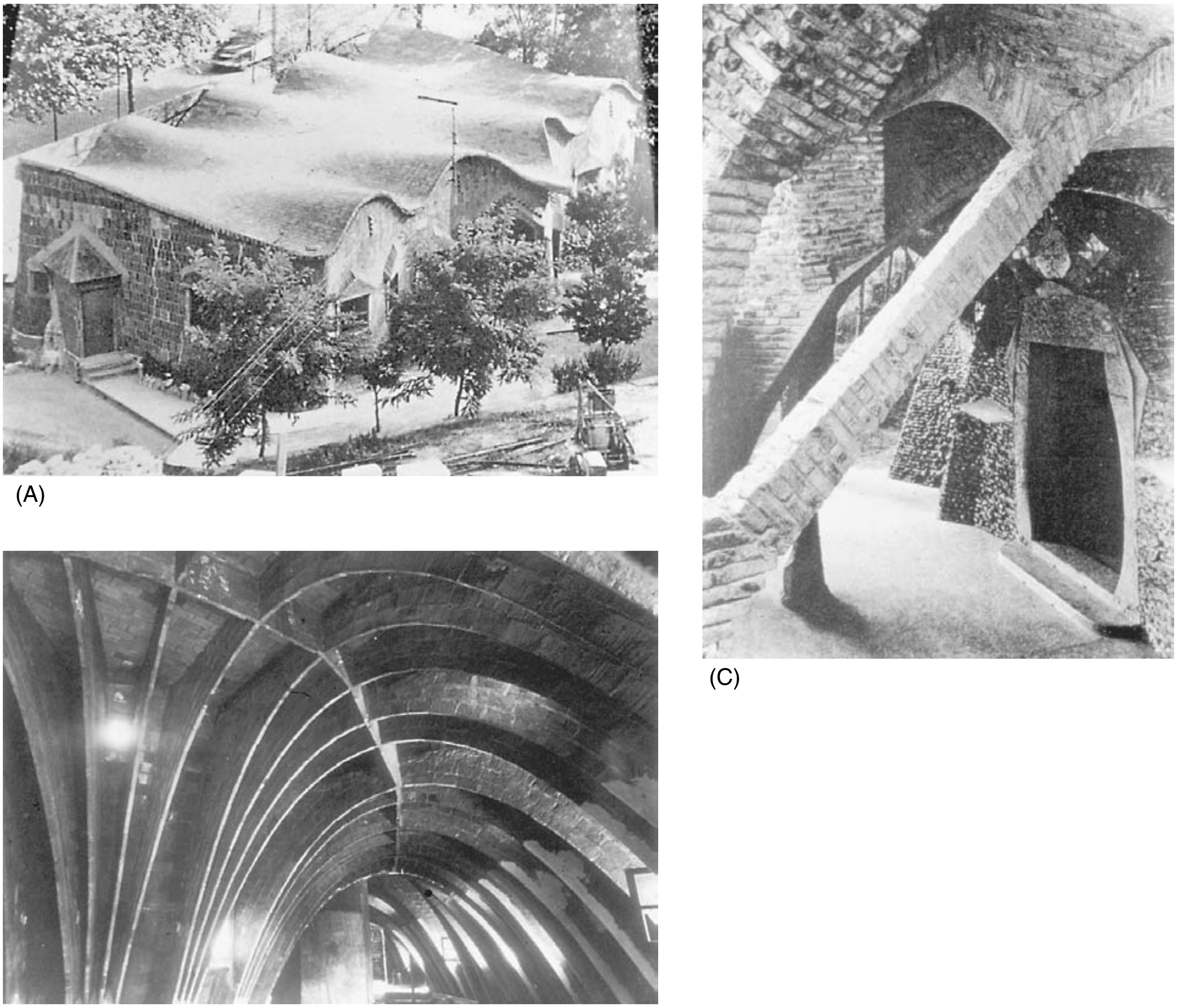
The first reinforced concrete building, the Eddystone Lighthouse (1774), was actually constructed of both concrete *and* stone, but the use of iron or steel as reinforcing was soon limited almost entirely to concrete. A few reinforced brick masonry structures were built in the early to mid-nineteenth century, but these experiments had been abandoned by about 1880. Reinforced masonry design was at that time intuitive or empirical rather than rationally determined, and rapid advances in concrete engineering quickly outpaced what was seen as an outmoded, inefficient, and uneconomical system. Even by the time the Monadnock Building was constructed, building codes still recognized lateral resistance of masonry walls only in terms of mass, and this did indeed make the system expensive and uneconomical.

1.3 REVIVAL

In the early 1920s, economic difficulties in India convinced officials that alternatives to concrete and steel structural systems had to be found. Extensive research began into the structural performance of reinforced

Figure 1-2 The Monadnock Building in Chicago (1891, Burnham and Root architects) was the last unreinforced high-rise masonry building. (*Photo courtesy of the School of Architecture Slide Library, the University of Texas at Austin.*)

masonry, which led not only to new systems of low-cost construction, but also to the first basic understanding of the structural behavior of masonry. It was not until the late 1940s, however, that European engineers and architects began serious studies of masonry bearing wall designs—almost 100 years after the same research had begun on concrete bearing walls.



(A)

(B)

(C)

Figure 1-3 Gaudi's innovative masonry structures: (*A*) warped masonry roof, Schools of the Sagrada Familia Church; (*B*) thin masonry arch ribs, Casa Mila; and (*C*) inclined brick column, Colonia Guell Chapel. (*Photos courtesy of the School of Architecture Slide Library, the University of Texas at Austin.*)

By that time, manufacturers were producing brick with compressive strengths in excess of 8000 psi, and portland cement mortars had strengths as high as 2500 psi. Extensive testing of some 1500 wall sections generated the laboratory data needed to develop a rational design method for masonry. These studies produced the first reliable, mathematical analysis of a very old material, freed engineers for the first time from the constraints of empirical design, and allowed formulation of rational structural theories. It was found that no new techniques of analysis were required, but merely the application of accepted engineering principles already being used on other systems.

The development of recommended practices in masonry design and construction in the United States took place during the decade of the 1950s, and resulted in publication of the first "engineered masonry" building code in 1966. Continued research throughout the following two decades brought about refinements in testing methods and design procedures, and led to the adoption of engineered masonry structural systems by all of the major building codes in the United States. Laboratory and field tests have also identified and defined the physical properties of masonry and verified its excellent performance in fire control, sound attenuation, and thermal resistance.

Masonry construction today includes not only quarried stone and clay brick, but a host of other manufactured products as well. Concrete block, cast stone, structural clay tile, terra cotta, glass block, mortar, grout, and metal accessories are all a part of the mason's trade. In various definitions of masonry, this group of materials is often expanded to include concrete, stucco, or precast concrete. However, the most conventional application of the term "masonry" is limited to relatively small building units of natural or manufactured stone, clay, concrete, or glass that are assembled by hand, using mortar, dry-stacking, or mechanical connectors.

1.4 CONTEMPORARY MASONRY

Contemporary masonry may take one of several forms. Structurally, it may be divided into loadbearing and non-loadbearing construction. Walls may be of single- or multi-wythe design. They may also be solid masonry, solid walls of hollow units, or cavity walls. Finally, masonry may be reinforced or unreinforced, and either empirically or analytically designed. Loadbearing masonry supports its own weight as well as the dead and live loads of the structure, and all lateral wind and seismic forces. Non-loadbearing masonry also resists lateral loads, and veneers may support their own weight for the full height of the structure, or be wholly supported by the structure at each floor. Solid masonry is built of solid units or fully grouted hollow units in multiple wythes with the collar joint between wythes filled with mortar or grout. Solid walls of hollow units have open cores in the units, but grouted collar joints. Cavity walls have two or more wythes of solid or hollow units separated by an open collar joint or cavity at least 2 in. wide (*see Fig. 1-4*). Masonry veneers are applied over non-masonry backing walls.

Empirical designs are based on arbitrary limits of height and wall thickness. Engineered designs, however, are based on rational analysis of the loads and the strength of the materials used in the structure. Standard calculations are used to determine the actual compressive, tensile, and shear stresses, and the masonry designed to resist these forces. Unreinforced masonry is still sometimes designed by empirical methods, but is applicable only to low-rise structures with modest loads. Unreinforced masonry is strong in compression, but weak in tension and flexure (*see Fig. 1-5*). Small lateral loads and overturning moments are resisted by the weight of the wall. Shear and flexural stresses are resisted only by the bond between mortar and units. Where lateral loads are higher, flexural strength can be increased by solidly grouting reinforcing steel into hollow unit cores or wall cavities wherever design analysis indicates that tensile stress is developed. The cured grout binds the masonry and the steel together to act as a single load-resisting element.

Contemporary masonry is very different from the traditional construction of earlier centuries. Its structural capabilities are still being explored as continuing research provides a better understanding of masonry structural behavior. Contemporary masonry buildings have thinner, lighter-weight, more efficient structural systems and veneers than in the past, and structures designed in compliance with current code requirements perform well, even in cases of significant seismic activity and extreme fire exposure.

1.5 COMMON CONCERNS

Although there is continuing structural research aimed at making masonry systems stronger, more efficient, and more economical, many of the concerns

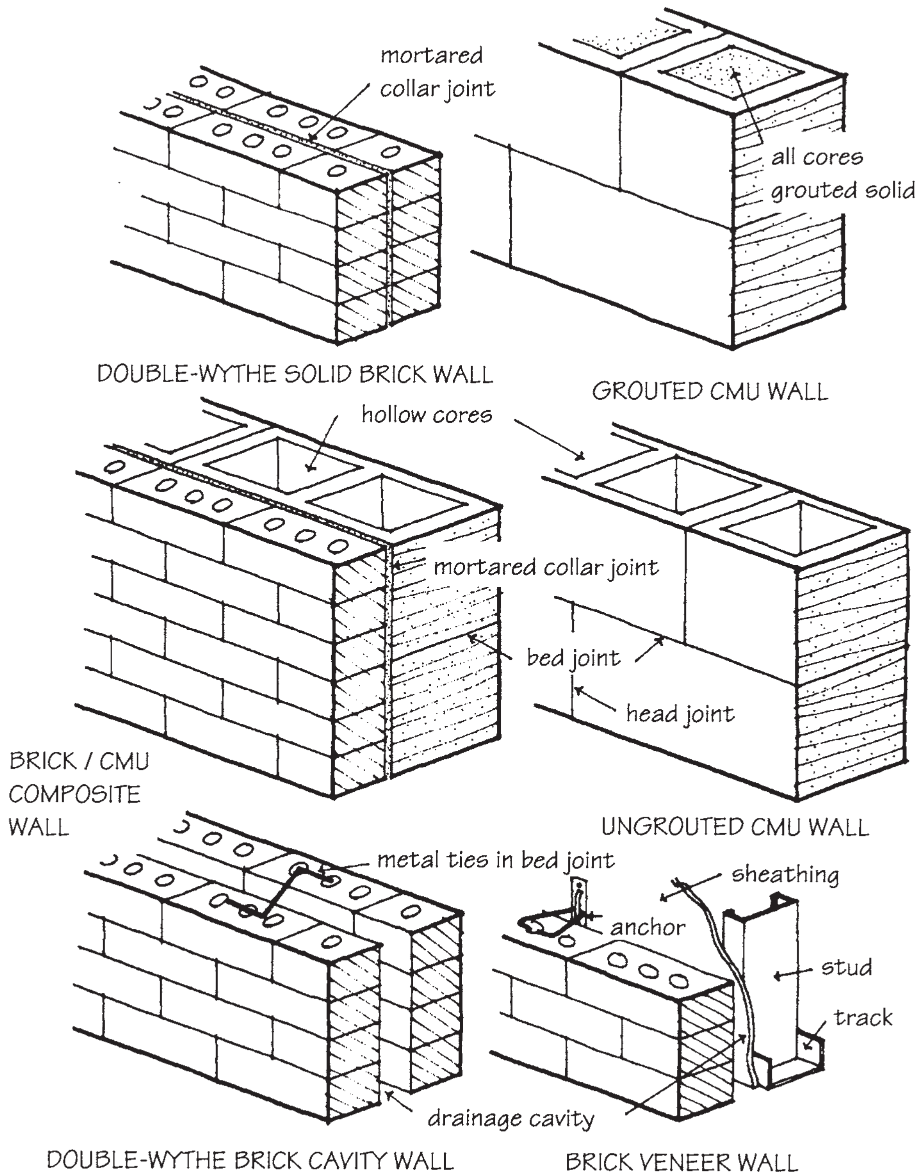


Figure 1-4 Examples of masonry wall types.

commonly expressed by both design professionals and contractors are related to weather resistance. Moisture penetration and durability, in fact, seem to be more significant day-to-day issues for most than structural performance. Building codes, which have traditionally provided minimum performance requirements only for structural and life safety issues, are now beginning to address water penetration, weather resistance, and durability issues for masonry as well as other building systems.

Contemporary masonry walls are more water permeable than traditional masonry walls because of their relative thinness, and more brittle because of the portland cement that is now used in masonry mortar. As is the case with any material or system used to form the building envelope, the movement of moisture into and through the envelope has a significant effect on the performance of masonry walls. Contemporary masonry systems are designed, not with the intent of providing a barrier to water penetration, but as drainage walls in which penetrated moisture is collected on flashing membranes and

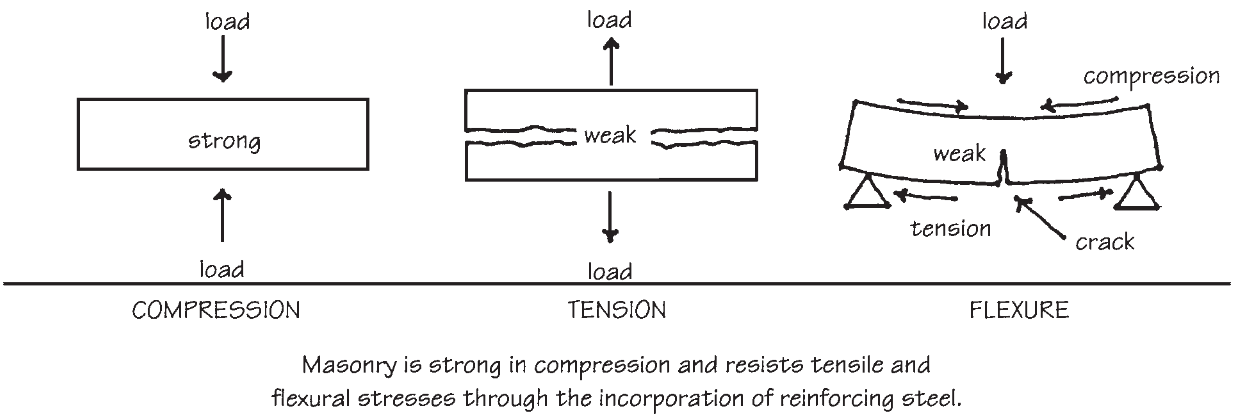


Figure 1-5 Compressive, tensile, and flexural strength of masonry.

expelled through a series of weep holes. Higher-performance wall systems for extreme weather exposures can be designed as pressure-equalized rain screens, but at a higher cost than drainage walls. Design, workmanship, and materials are all important to the performance of masonry drainage and rain screen walls:

- Mortar joints must be full
- Mortar must be compatible with and well bonded to the units
- Drainage cavity must be kept free of mortar droppings
- Appropriate flashing material must be selected for the expected service life of the building
- Flashing details must provide protection for all conditions
- Flashing must be properly installed
- Weep holes must be properly sized and spaced
- Weep holes must provide rapid drainage of penetrated moisture

With adequate provision for moisture drainage, masonry wall systems can provide long-term performance with little required maintenance. The chapters which follow discuss materials, design, and workmanship with an eye toward achieving durability and weather resistance as well as adequate structural performance in masonry systems.

2 RAW MATERIALS AND MANUFACTURING PROCESSES

The quality and characteristics of masonry products are directly and exclusively determined by the raw materials and methods of manufacture used in their production. A basic introduction to this aspect of masonry will aid in understanding the finished products and how they may best be used in specific design applications.

2.1 CLAY MASONRY

Clay, the raw material from which brick, structural clay tile, and terra cotta are made, is the most plentiful natural substance used in the production of any building product. Clay is the end product of the chemical alteration over long periods of time of the less stable minerals in rock. This chemical weathering produces minute particles that are two-dimensional or flake-shaped. The unique plastic characteristics of clay soils are a result of the enormous amount of surface area inherent in this particle size and shape. The natural affinity of clay soils and moisture results in cohesiveness and plasticity from the surface tension of very thin layers of water between each of these minute particles. It is this plasticity which facilitates the molding and shaping of moist clay into usable shapes.

For the architect, the importance of understanding clay characteristics and methods of manufacture is their relationship to finished appearance and physical properties. Color depends first on the composition of the raw material and the quantitative presence of metallic oxides. Second, it is an indication of the degree of burning to which the clay has been subjected. Lighter-colored units (called salmons) for a given clay are normally associated with under-burning. They may also be indicative of high porosity and absorption along with decreased strength, durability, and resistance to abrasion. On the other hand, the very dark colored units (called clinkers) produced from the same clay result from over-burning. This indicates that the units have been pressed and burned to a very high compressive strength and abrasion resistance, with greatly reduced absorption and increased resistance to freezing and thawing.

Most of the brick used in building construction falls between the extremes of salmon and clinker brick. Since clay composition is the primary determinant of brick color, lightness or darkness cannot be used as an absolute indicator of physical properties for brick made from different raw materials. It can, however, assist generally in the evaluation and selection of brick to meet specific design or exposure requirements.

2.1.1 Clay Composition

Clays are basically compounds of silica and alumina with varying amounts of metallic oxides and other minor ingredients and impurities. Metallic oxides act as fluxes to promote fusion at lower temperatures, influence the range of temperatures in which the material vitrifies, and give burned clay the necessary strength for structural purposes. The varying amounts of iron, calcium, and magnesium oxides also influence the color of fired clay.

Clays may be classified as either calcareous or non-calcareous. While both are hydrous aluminum silicates, the calcareous clays contain around 15% calcium carbonate, which produces a yellowish color when fired. The non-calcareous clays are influenced by feldspar and iron oxide. The oxide may range from 2 to 25% of the composition, causing the clay to burn from a buff to a pink or red color as the amount increases.

Any lime that is present in a clay must be finely crushed to eliminate large lumps. Lime becomes calcined in the burning process and later slakes or combines with water when exposed to the weather, so that any sizable fragments will expand and possibly chip or spall the brick.

2.1.2 Clay Types

There are three different types of clay which, although they are similar in chemical composition, have different physical characteristics. Surface clays, shales, and fire clays are common throughout the world, and result from slight variations in the weathering process.

Surface clay occurs quite close to the earth's surface, and has a high oxide content, ranging from 10 to 25%. Surface clays are the most accessible and easily mined, and therefore the least expensive.

Shale is a metamorphic form of clay hardened and layered under natural geologic conditions. It is very dense and harder to remove from the ground than other clays, and as a result, is more costly. Like surface clay, shale contains a relatively high percentage of oxide fluxes.

Fire clay is formed at greater depths than either surface clay or shale. It generally has fewer impurities, more uniform chemical and physical properties, and only 2 to 10% oxides. The lower percentage of oxide fluxes gives fire clay a much higher softening point than surface clay and shale, and the ability to withstand very high temperatures. This refractory quality makes fire clay best suited to producing brick and tile for furnaces, fireplaces, flue liners, ovens, and chimney stacks. The low oxide content also causes the clay to burn to a very light brown or light buff color, approaching white.

Clay is well suited to the manufacture of masonry products. It is plastic when mixed with water, and easily molded or formed into the desired shapes; it has sufficient tensile strength to maintain those shapes after the dies or molds are removed; and its particles are ceramically fused at high temperatures.

2.1.3 Material Preparation

Brick plants commonly mine from several clay pits at a time. Since the raw clay is not always uniform in quality and composition, two or more clays from different pits or from remote locations within the same pit are blended to minimize much of the natural variation in chemical composition and physical properties. Blending produces a higher degree of product uniformity, helps control the color of the units, and permits some latitude in providing raw material suitable for specific types of brick or special product requirements. The clay is first washed to remove stones, soil, or excessive sand, then crushed into smaller pieces, and finally ground to a powdered mix. Particle size is carefully controlled so that only the finer material is taken to storage bins or directly to the forming machine or pug mill for tempering and molding.

2.1.4 Manufacturing

After preparation of the raw clay, the manufacture of fired brick is completed in four additional stages: *forming, drying, burning,* and *drawing and storage* (*see Fig. 2-1*). The basic process is always the same, and differences occur only in the molding techniques. In ancient as well as more recent history, brick was exclusively hand-made. Since brick-making machines were invented in the late nineteenth century, however, most of the structural clay products manufactured in the United States are machine-made by one of three forming methods: *stiff-mud, soft-mud,* or *dry-press.*

2.1.5 Forming

The first step in each forming method is tempering, where the clay is thoroughly mixed with a measured amount of water. The amount of water and the desired plasticity vary according to the forming method to be used.

The *stiff-mud extrusion method is used for more than 80% of the brick manufactured in the United States.* A minimum amount of water, generally 12 to 15% moisture by weight, is mixed with the dry clay to make it plastic. After thorough mixing in a pug mill, the tempered clay goes through a de-airing process which increases the workability and plasticity of the clay and produces units with greater strength. The clay is then forced through a steel die in a continuous extrusion of the desired size and shape, and at the same time, is cored to reduce weight and to facilitate drying and burning. Automatic cutting machines using thin wires attached to a circular steel frame cut the extruded clay into pieces (*see Fig. 2-2*). Since the clay will shrink as it is dried and burned, die sizes and cutter wire spacing must be carefully calculated to compensate. Texturing attachments may be affixed to roughen, score, scratch, or otherwise alter the smooth skin of the brick column as it emerges from the die (*see Fig. 2-3*). After cutting, a clay slurry of contrasting color or texture may also be applied to the brick surface to produce different aesthetic effects.

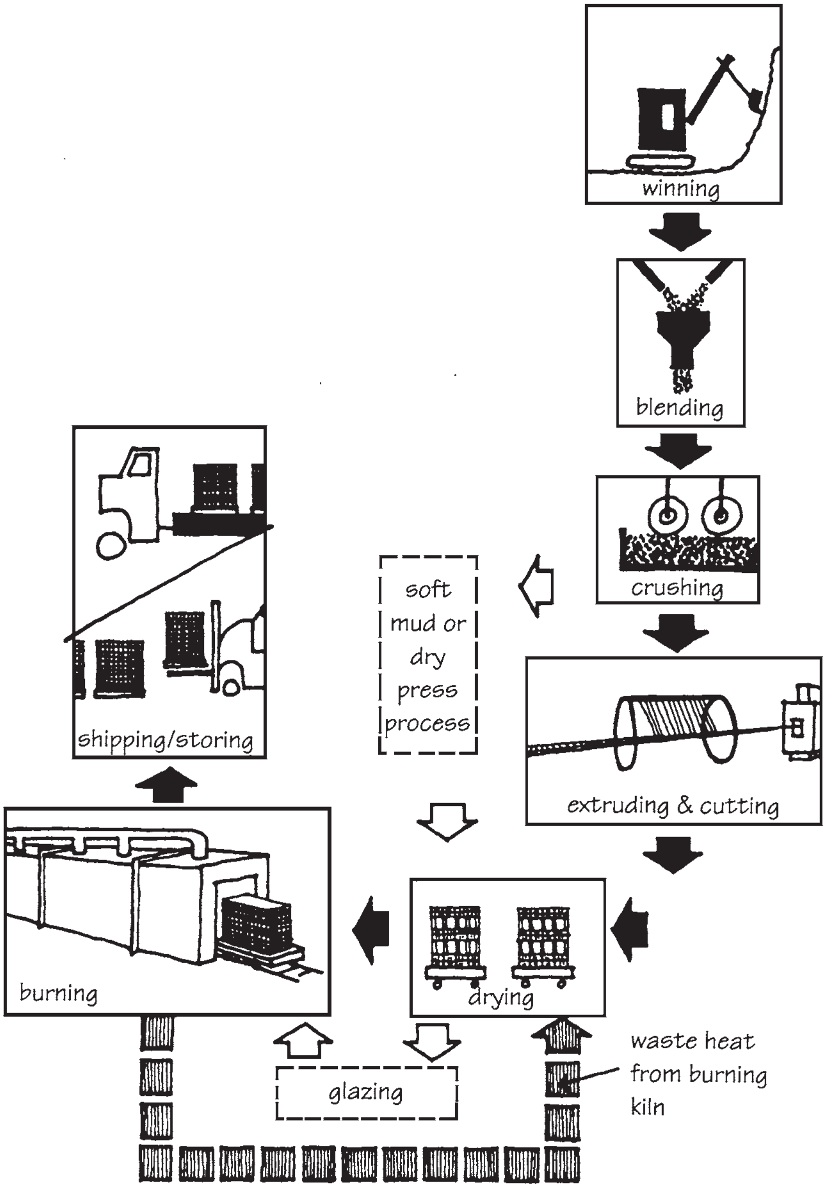


Figure 2-1 Brick manufacturing process.

A conveyor belt moves the "green" or wet brick past inspectors, who remove imperfect units and return them to the pug mill. Satisfactory units are moved from the conveyor to dryer cars and stacked in a prescribed pattern to allow free flow of air and kiln gases for burning. The stiff-mud process produces the hardest and most dense of the machine-made bricks, and also delivers the highest volume of production.

The *soft-mud method* of production is the oldest, and was used exclusively up until the nineteenth century (*see Fig. 2-4*). All hand-made brick is formed by this process even today. Only a few manufacturers still produce genuine hand-made brick, but demand is increasing as more historic restoration projects are undertaken.

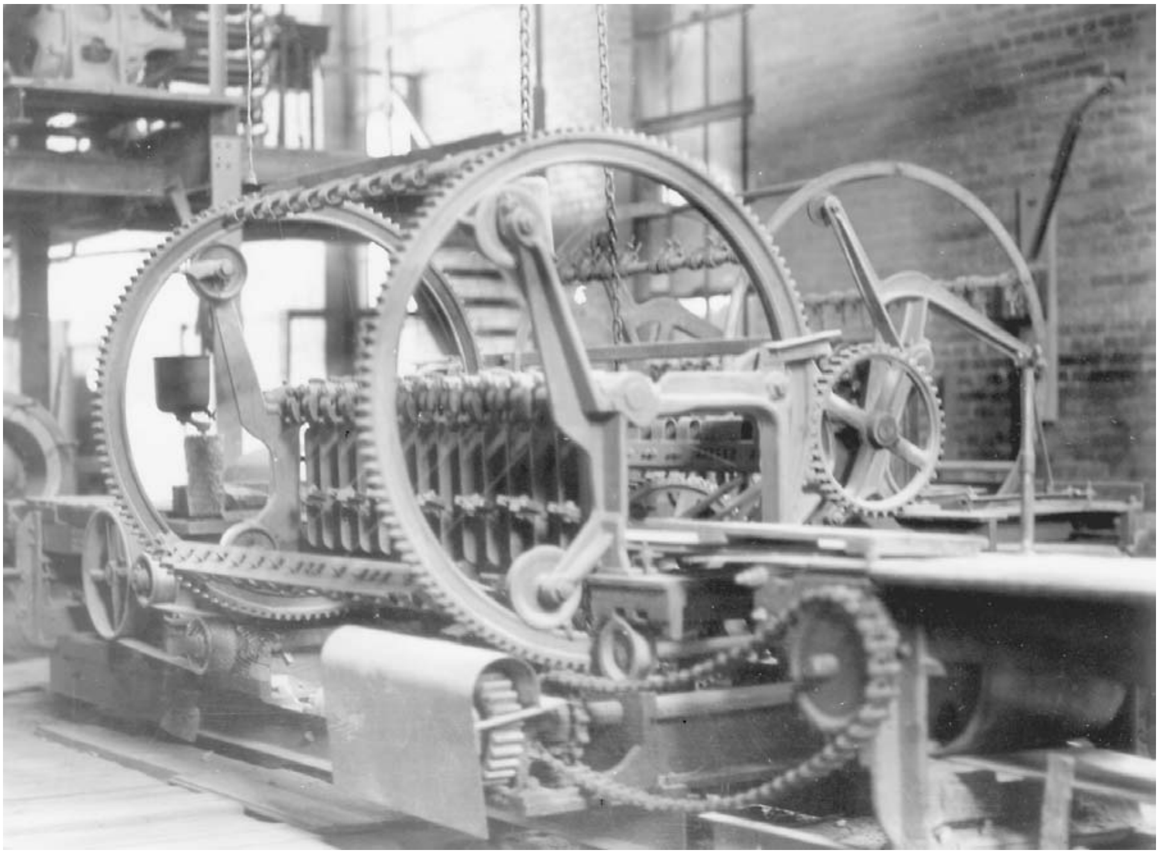


Figure 2-2 Wire-cutting extruded, stiff-mud brick. (*Photo courtesy BIA.*)

Automated machinery can accomplish soft-mud molding more uniformly and efficiently than hand work, and is now widely used. The soft-mud process is particularly suitable for clays which contain too much natural water for the extrusion method. The clay is tempered to a 20 to 30% moisture content (about twice that of the stiff-mud clays) and then pressed into wooden molds by hand or machine to form standard or special shapes. To prevent the clay from sticking, the molds are lubricated with sand or water. The resulting "sand-struck" or "water-struck" brick has a unique appearance characterized by either a rough, sandy surface or a relatively smooth surface with only slight texture variations from the individual molds (*see Fig. 2-3*). In addition to having an attractive rustic appearance, soft-mud units are more economical to install because less precision is required, and bricklayers can usually achieve a higher daily production. Manufacturers often simulate the look of hand-made brick by tumbling and roughening extruded brick.

The mortar bedding surfaces of sand-struck or sand-molded brick must be brushed clean of loose sand particles so that mortar bond is not adversely affected. Even if sand is not actually applied to the bed surfaces in the manufacturing process, stray particles along the edge of a unit can inhibit the critical mortar-to-unit bond at the weathering face of a wall, creating an unwanted increase in moisture penetration.