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A b s t r a c t

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**"A H I S T O R Y O F C I V I L
E N G I N E E R I N G"**

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thing, and that function has continued to this day. The very
root of the word, "ingenium," by indicates the engineer's position
in society; it is to **Charles J. Merdinger**. The aim of the
scientist is to know, **Brasenose College** engineer is to do by
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resulted in a more efficient utilization of materials and has
given rise to the oft-quoted definition of engineering as "the
art of doing with one dollar what five bunglers can do with five
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Derived from the Latin "ingenium," which means natural capacity or invention, the word "engine" provides a clue as to the origin of the title "engineer." Ingenium, engine, military engine, and military engineer follow each other logically when the assault and defense of early walled cities is considered. It is likely that the word "engineer" was derived from "engine" in much the same manner that "musketeer" was derived from "musket," for the early duties of the military engineer were largely concerned with making and operating engines of war such as catapults, battering rams, and the like. It naturally fell his lot to devise defenses against these weapons as well, so we find the engineer branching out into the building of fortifications and other works to resist or aid seige. In time the engineer's job came to include all types of construction, such as roads and bridges, needed to facilitate the movements of an army. In every case his primary task as an engineer was to contrive or to build something, and that function has continued to this day. The very root of the word, "ingenium," indicates the engineer's mission in society; it is to do, to act, or to make. The aim of the scientist is to know, but the aim of the engineer is to do by applying science to his work. This application of science has resulted in a more efficient utilization of materials and has given rise to the oft-quoted definition of engineering as "the art of doing with one dollar which any bungler can do with two after a fashion."

The first man on record to call himself a "civil" engineer

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was the eighteenth century Englishman John Smeaton, who sought to distinguish his civilian construction work from that of the military engineer. Just what constituted civil engineering remained a rather indefinite concept until the profession was defined in the charter granted in 1828 to the Institution of Civil Engineers at London as: "---the art of directing the great sources of power in nature for the use and convenience of man, as the means of production and of traffic in states, both for external and internal trade, as applied in the construction of roads, bridges, aqueducts, canals, river navigation and docks for internal intercourse and exchange, and in the construction of ports, harbours, moles, breakwaters and lighthouses, and in the art of navigation by artificial power for the purposes of commerce, and in the construction and application of machinery, and in the drainage of cities and towns." The term "civil" engineer gradually became restricted to those who concerned themselves chiefly with works of a static nature such as roads and tunnels, while those who concerned themselves primarily with the operation of moving machinery adopted the designation "mechanical" engineer. In time other specialties came to be recognized, and new branches such as "chemical" and "electrical" engineering were born. A century after the granting of the 1828 charter civil engineering had become only one of the many branches of the engineering profession and had changed somewhat in the fields it covered. Engineering had come to be defined as the "professional and systematic application of science to the efficient utilization of natural resources to produce wealth." The sub-fields of civil engineering officially adopted in 1929 by the

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California State Board of Engineering Examiners included the following: "highways, bridges, water supply, inland waterways, harbors, drainage, irrigation, water power, flood control, municipal improvements, railroads, tunnels, airports, airways, purification of water, sewage, refuse disposal, foundations, framed and homogeneous structures, buildings, city and regional planning, valuation and appraisals, and surveying (other than land surveying)."

In other ages and in other civilizations the engineer was known by other names--as a sage, architect, philosopher, or wise man--but his function was essentially that of his modern counterpart. Regardless of what he called himself or what other duties he performed in the past, we shall try to trace the engineer and his works from earliest times to the present. In a sense, the story of engineering is a story of mankind, for no less than law and government has technology been a mark of the civilized world. The archaeological and historical evidence thus far is too meager to permit us to deal at length on the progress of civil engineering in most of the civilizations which have previously flourished. The work of many of the civilizations, as for instance the Andean, has been here omitted--even though some evidence is available--for it seems to bear little or no relationship to the main thread of this history. Relatively little space, then, has been assigned to the history of civil engineering elsewhere than in the Hellenic and Western world, for our main task is to trace the traditions of the profession which have culminated in the civil engineering of the twentieth century.

Perhaps the clearest way to present the history of this

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profession is to review briefly the development of engineering as a whole through every age and then go back and develop each section of the profession in the following order: materials and building construction, roads, bridges, canals, tunnels, surveying, water supply, sewerage, hydraulic and coastal works, and railroads. According to present evidence, the first traces of what might be called civil engineering appeared in Egypt commencing somewhere around 3000 B.C. Surveying, hydraulic works, and building construction made up the bulk of Egyptian engineering, but it is doubtful whether these had any direct effect on the works of succeeding or contemporary civilizations. The most significant thing about Egyptian engineering is that here, for the first time, we have evidence of man building to a plan instead of haphazardly and using mathematics to ensure the results desired. This contribution is slight when compared with the works of modern civil engineering but gigantic when compared to the works of primitive man.

The next people of importance to this study were the Greeks, whose main contributions to civil engineering were theoretical rather than practical, for they did much to develop the mathematics and geometry which later became so important in engineering. This emphasis of theoretical over practical was due in part to the attitude of the philosophers who led Greek thought; it was due in greater measure to the country's geography--or to be more precise, its topography--which in turn shaped its political and economic life. The construction of vast public works, consistent with the technology of the times, could not be justified from an administrative or commercial standpoint, and so

they were never brought into being.

With the emergence of Rome as the dominant power in the world, civil engineering reached a peak it did not again achieve until the nineteenth century. Parts of the old Roman roads still survive to this day, and this permanence and solidity which manifested itself in their roads was a characteristic which extended throughout all of their engineering endeavors. Aqueducts, bridges, tunnels, canals, and all forms of hydraulic works fell within the scope of the Roman engineers during the time of the republic and later under the emperors. In the Roman structures we find definite evidence of the use of mathematics and geometry in their lay-out and construction. Closer inspection reveals that they were over-designed--by modern standards at least--a further indication that they were derived more from rule-of-thumb methods than from basic scientific principles. As Rome was on the ascendancy engineering was alternately an effect and cause of strong government, but when the government began to break down technology could not save it. The engineers did not at first lose their skill and know-how, they simply lost the funds to maintain the works they had built. Thus, along with the other hall-marks of an advanced civilization, the art of civil engineering slowly died among the crumbling ruins of the Roman empire in the fifth century.

Following the fall of Rome, a flicker of learning and engineering skill was kept alive in the Arab world, but little new was added. The importance of the Arabic civilization rests in the fact it served as the "funnel" into which the knowledge of Greece, the Near East, and to some extent India and even

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China passed. Here it was absorbed and passed on to the Western world of the Middle Ages. A revival in Western engineering, crude though it was, was initiated in the medieval monasteries. In the twelfth century we find pious monks in Italy, France, and England taking up the task of building bridges and other works modeled after Roman remains. Monastery water supply and drainage systems also began to appear about this time as did the great Gothic cathedrals which still excite our admiration. The later Middle Ages were also marked by the construction of irrigation and drainage canals in both Holland and Italy, and for generations Dutch and Italian engineers were regarded as supreme in all types of hydraulic work. In time, the ecclesiastics passed their knowledge and skills to the laity in the great period of enlightenment which followed.

Except in the field of architecture and building construction, the Renaissance was more a time of ideas than of action insofar as it affected the engineering profession. The new pattern of thought engendered by the Renaissance bore fruit in the brilliant scientific speculations of the philosophers of the seventeenth century--a century marked by the contributions of some of the brightest names in science, namely Gilbert, Kepler, Hooke, Torricelli, Pascal, Boyle, Huygens, and Newton. In the strictest sense, these philosophers were not engineers, but their findings helped to establish a theoretical base for the art of scientific engineering which was to follow. The seventeenth century philosophers were followed--in England especially--by the "practical" men of the eighteenth century who made a start in translating scientific theory into practice.

Early in the nineteenth century modern civil engineering began.

Barge canals, which had been the main civil engineering ventures of the eighteenth century, gave way to the railroads shortly after the opening of the Liverpool and Manchester Railway in 1830. As had the canals which preceded them, the new railroads brought about increased improvements in bridge and tunnel construction. A more scientific approach to road-making also was manifested early in the century, and harbor and waterfront construction kept abreast of other developments in the profession. Large cities, spawned by the Industrial Revolution, soon found their water supplies inadequate, both as to quality and quantity, and here again the skill of the engineer was brought into play for the good of the community. In like manner, stream pollution in industrial areas toward the latter part of the century brought about the need for sewerage reform, a problem which was essentially solved as the century drew to a close. The commercial development of Portland cement and steel was another factor of great importance during this period for a whole new field of design and construction was now opened. It was not until the twentieth century, however, that the great possibilities of these materials came to be realized. New problems in engineering were ushered in with the twentieth century as the automobile and airplane entered the transportation field, but, as had been the case before, the profession proved flexible enough to meet successfully the new challenges.

The rapid changes brought about in the nineteenth century naturally raise a question as to when the emphasis in engineering design shifted from calculations based on rule of thumb

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to those based on truly scientific principles. Actually, the time when this shift in emphasis became significant did not coincide with the beginning--according to our definition--of modern civil engineering. We associate the beginning of modern civil engineering with the name of Telford and with the incorporation of Great Britain's Institution of Civil Engineers in 1828--the time when civil engineering came to be formally recognized as a profession both by its members and by the outside world. At the time of its recognition as a profession, engineering still had most of its roots of design in "practical" rather than in scientific principles. By the middle of the nineteenth century, however, the shift to the scientific emphasis in design had become apparent. Squire Whipple's first treatise on stresses in trusses (1847) and De Sazilly's analysis of dam design (1853) marked the beginning of truly rational and scientific design in engineering. From this time forward, design passed out of the hands of the "practical" men into the hands of those with scientific training, and progress leaped forward at an astounding pace during the latter half of the nineteenth century.

In glancing over the progress of civil engineering we find that in every case of outstanding achievement the same factors have been in evidence. First of all, topography has been favorable in initial instances, tough enough to evoke a response but gentle enough to be overcome. Aided by their increased confidence and guided by their past experience, engineers from a country with such topography have been able to go into areas of men as well.

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increasing topographical difficulty and master conditions which would have been impossible to master had they attempted to lay the foundations of their skill there. The effect of climate has been similar. Practically all engineering knowledge has originated with people from temperate climates who have neither been all but overwhelmed by arctic blasts nor enervated by tropic heat. Another decisive factor has been wealth, both in the form of workable materials and in the form of financial backing. The first depends on nature, but the second may stem from government or private enterprise. Regardless of the source of the financial backing, however, government must be regarded as another factor, for only under relatively stable political organizations has true engineering progress been made. Commercial benefits have provided much of the incentive in engineering, but a great measure of credit must also be given to those men of public spirit who have, with no thought of financial gain, labored to make this a better world in which to live. The combination of all these factors has encouraged engineering development where the need of rational thought has been firmly planted. From thought has come knowledge, and from knowledge, power-- power of man over his environment. In the final analysis, the effect of the engineer on his environment and the effect of the environment on the engineer cannot be separated. One has continually acted and reacted on the other until cause and effect are hopelessly intermingled. One fact emerges clear, however; the engineer has played a leading role not only in changing the face of the earth but in shaping the destiny of nations and of men as well.

A
HISTORY
OF
CIVIL ENGINEERING

by
Charles J. Merdinger
Oxford

In Three Volumes
Vol. I

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...of war, war itself, as the aftermath of war gave birth to a great many histories, books of travel which were supposed to glorify the victories of peace. There were also books on the conduct of art, music, social science, and so on, and a host of other fields of human endeavor which were supposed to be the result of a struggle for a better life. Although, through all this, in an age of technology, very little has been written on the history of engineering--or even, incidentally, little has been written on history of its parent branch, civil engineering.

It is not our purpose here to explain why this has been so, although a few points need serious thought. Prior to the latter part of the nineteenth century few engineers left written records of their works; they were content to let their engineering works speak for themselves. In the main, the engineer of the twentieth century has continued somewhat along the same lines, confining his relatively few writings to narrow technical and specialized fields of study to be given...

subjects. The lack of any FOREWORD

History, that branch of knowledge which records and explains past events, has concerned itself to a large extent with the trials and tribulations of kings and princes, warriors and statesmen, Church and State; it has told, for the most part, the story of the turmoils of the past. Significant dates still memorized by schoolboys are those marking wars, battles, dynasties, and change of governments. Relatively recent historians have added to the traditional fields of political and armed strife that of economic strife, and some have gone so far as to trace practically all causes back to an economic source. Though the threats of war, war itself, or the aftermath of war have dominated a great many histories, there are those which have sought to glorify the victories of peace. Such works have traced the development of art, music, social customs, science, and a host of other fields of human endeavor which have been significant in man's struggle for a better life. Strangely enough, though we are living in an age of technology, very little has been written on the history of engineering--or more specifically, little has been written on history of its parent branch, civil engineering.

It is not our purpose here to enquire why this has been so, although a few points seem obvious enough. Prior to the latter part of the nineteenth century few engineers left written accounts of their works; they were content to let their engineering works speak for themselves. In the main, the engineer of the twentieth century has continued somewhat along the same lines, confining his relatively few writings to narrow technical and specialized

word of caution is in order here.

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subjects. The lack of non-technical writings on engineering has made it difficult for the regular historian to give a true picture of how engineering has developed, and so he has, for the most part, left the subject alone. The average engineer is too engrossed in the work at hand and in the new theories and techniques coming out every day to concern himself with the historical aspects of his profession, and so he, too, has left the subject alone. Therefore, the writer who attempts to develop the history of civil engineering sets for himself a difficult, practically uncharted course, liable to the rocks and shoals of isolated, seemingly unrelated facts and no facts at all, a headache to the engineer and historian alike.

This work is an engineer's attempt to piece together fragments of technical and non-technical knowledge in such a manner as to trace logically the rise of civil engineering from pre-historic times to the present day. The first chapter briefly summarizes the main influences upon and the main developments in civil engineering throughout the ages. Little attempt has been made to prove many of the statements made in this first chapter, for these proofs come more logically in the later chapters. Each of the following chapters takes up one branch of civil engineering, such as roads, bridges, or canals, and traces the development of that particular branch from its earliest days to the present. The emphasis has been placed upon the internal development of engineering rather than upon the external influence of engineering change on our political and economic life. Since the development of most technological advances has come as the result of the labors of many spread over a period of years, a word of caution is in order here. In every case where the

"first" operation or idea is mentioned, it should be noted that it is the first operation or idea known to the author which is considered by him or by others to be significant from the standpoint of subsequent development. This book is addressed primarily to the civil engineer, but the language used is sufficiently non-technical to allow non-engineers to follow the lines of thought without difficulty. It is hoped that this work will be of some help in filling in that part of the education of the engineer which has so long been neglected, a knowledge of the long traditions and struggles which have culminated in the profession of civil engineering in the twentieth century.

Chapter I

CIVIL ENGINEERING THROUGH THE AGES C.J.M.

Chapter I

CIVIL ENGINEERING THROUGH THE AGES

vast machine CIVIL ENGINEERING THROUGH THE AGES

beams with the necessary tackle, which striking with a tremendous force on the enemy's Introduction

hoisted up at the prows by iron slant or beam like the masts of

Derived from the Latin "ingenium," which means natural capacity or invention, the word "engine" provides a clue as to the origin of the title "engineer." Ingenium, engine, military engine, and military engineer follow each other logically when the assault and defense of early walled cities is considered. It is likely that the word "engineer" was derived from "engine" in much the same manner that "musketeer" was derived from "musket," for the early duties of the military engineer were largely concerned with making and operating engines of war such as catapults, battering rams, and the like. It naturally fell his lot to devise defenses against these weapons as well, so we find the engineer branching out into the building of fortifications and other works to resist or aid seige. The classic example of the works of the engineer in ancient times was described by Plutarch in his "Life of Marcellus":

When the Romans attacked them (the Syracusans) both by sea and land, they were struck dumb with terror, imagining that they could not possibly resist such numerous forces, and so furious an assault. But Archimedes soon began to play his engines, and they shot against the land-forces all sorts of missive weapons and stones of an enormous size with so incredible a noise and rapidity, that nothing could stand before them; overturning and crushing whatever came in their way, and spreading terrible disorder throughout the ranks. On the side toward the sea were erected

vast machines, thrusting forth on a sudden over the walls huge beams with the necessary tackle, which striking with a prodigious force on the enemy's galleys sunk them at once: while other ships, hoisted up at the prows by iron claws or hooks like the beaks of cranes, and set upright on the stern, were plunged to the bottom of the sea; and others again by ropes and grapples were drawn toward the shore, and after being whirled about, and dashed against the rocks that projected below the walls, were broken to pieces, and the crews perished. -----At last the Romans were so terrified, that if they saw but a rope or a stick put over the walls, they cried out 'Archimedes was levelling some machine at them;' and turned their backs and fled."

In time the engineer's job came to include all types of construction, such as roads and bridges, needed to facilitate the movements of an army. In every case his primary task as an engineer was to contrive or to build something, and that function has continued to this day. The very root of the word, "ingenium," indicates the engineer's mission in society; it is to do, to act, or to make. The aim of the scientist is to know, but the aim of the engineer is to do by applying science to his work. This application of science has resulted in a more efficient utilization of materials and has given rise to the oft-quoted definition of engineering as "the art of doing well with one dollar which any bungler can do with two after a fashion."

The first man on record to call himself a "civil" engineer was the eighteenth century Englishman John Smeaton, who sought to distinguish his civilian construction work from that of the military engineer. Just what constituted civil engineering

remained a rather indefinite concept until the profession was defined in the charter granted in 1828 to the Institution of Civil Engineers at London as: "----the art of directing the great sources of power in nature for the use and convenience of man, as the means of production and of traffic in states, both for external and internal trade, as applied in the construction of roads, bridges, aqueducts, canals, river navigation and docks for internal intercourse and exchange, and in the construction of ports, harbours, moles, breakwaters and lighthouses, and in the art of navigation by artificial power for the purposes of commerce, and in the construction and application of machinery, and in the drainage of cities and towns." The term "civil" engineer gradually became restricted to those who concerned themselves chiefly with works of a static nature such as roads and tunnels, while those who concerned themselves primarily with the operation of moving machinery adopted the designation "mechanical" engineer. In time various other specialties came to be recognized, and new branches such as "chemical" and "electrical" engineering were born. A century after the granting of the 1828 charter, civil engineering had become only one of the many branches of the engineering profession and had changed somewhat in the fields it covered. Engineering had come to be defined as "the professional and systematic application of science to the efficient utilization of natural resources to produce wealth." The sub-fields of civil engineering officially adopted in 1929 by the California State Board of Engineering Examiners included the following: "highways, bridges, water supply, inland waterways, harbors, drainage, irrigation, water power, flood control,

municipal improvements, railroads, tunnels, airports, airways, purification of water, sewage, refuse disposal, foundations, framed and homogeneous structures, buildings, city and regional planning, valuation and appraisals, and surveying (other than land surveying).

In other ages and in other civilizations the engineer was known by other names--as a sage, architect, philosopher, or wise man--but his function was essentially that of his modern counterpart

Regardless of what he called himself or what other duties he performed in the past, we shall try to trace the engineer and his works

from earliest times to the present. In a sense, the story of engineering is a story of mankind, for no less than law and govern-

ment has technology been a mark of the civilized world. Arnold J. Toynbee in "A Study of History" (abridged, London, 1946) recognizes

twenty-one "civilizations" in the history of the world, most of them related as parent or offspring to one or more of the others:

namely, the Andean, Babylonian, Central American (Mexican and Yucatec), Egyptian, Far Eastern-Japanese Offshoot, Far Eastern-Main Body,

Hellenic, Hindu, Hittite, Indic, Islamic (Arabic and Iranian), Mayan, Minoan, Orthodox Christian-Main Body, Orthodox Christian-Russian

Offshoot, Sinic, Sumerian, Syriac, and Western. He further counts as "abortive civilizations" the Far Eastern Christian, the Far

Western Christian, and the Scandinavian societies. His "arrested civilizations" include the Eskimos, the Nomads, the 'Osmanlis, the

Polynesians and the Spartans. The archaeological and historical evidence thus far is too meager to permit us to deal at length

on the progress of civil engineering in most of these societies. The work of many of these, as for instance the Andean, has been

here omitted--even though some evidence is available--for it seems to bear little or no relationship to the main thread of

this history. Relatively little space, then, has been assigned to the history of civil engineering elsewhere than in the Hellenic and Western world, for our main task is to trace the traditions of the profession which have culminated in the civil engineering of the twentieth century.

ENGINEERING OF THE ANCIENTS

It is generally accepted that in some parts of the world man had, by 4000 B.C., learned the use of fire, the working of flint, the manufacture of baskets, boats, clothing, houses, pottery, and weapons, and it is also probable that nowhere had he advanced much beyond that stage. During the next millennium, however, a gradual increase was made in social organization and technical achievement along the banks of the Nile in Egypt. To the semi-legendary founder of the First Dynasty, Menes (c 3200 B.C.), are attributed the first large-scale hydraulic works, drainage and irrigation alike. A brilliant period of activity soon followed in the five hundred years from 3000 to 2500 B.C., an era which witnessed among other things the erection of the pyramids. A crude form of surveying developed and elementary mathematics came to be used. The earliest known work on mathematics is a papyrus copied about 1550 B.C., but it describes operations which might date to the Old Kingdom (2980-2475 B.C.). Of particular interest to engineers is the fact that its author Ahmes used a decimal notation but no zero. For the next three thousand years civilization in Egypt showed alternate decline and revival,

but no appreciable advance was made in the art of civil engineering in this period. The outstanding engineering feature of the Middle Empire appears to have been the construction of rock-cut tombs, while huge masonry temples marked the contribution of the great Theban kingdom which arose about 1700 B.C. Surveying, hydraulic works, and building construction, then, made up the bulk of early Egyptian engineering, but it is doubtful whether these had any direct effect on the works of succeeding or contemporary civilizations. The most significant thing about Egyptian engineering is the fact that here, for the first time, we have evidence of man building to a plan instead of haphazardly and using mathematics to ensure the results desired. This contribution is slight when compared with the works of modern civil engineering but gigantic when compared to the works of primitive man.

Early civilizations also sprang up in the valleys of the Indus and of the Tigris and Euphrates, but the small knowledge we have of them makes it difficult to evaluate their contributions to the development of engineering. Even when we come to the Minoan civilization in the Aegean, our task is still difficult. Recent finds by archaeologists have revealed that these people--who probably flourished between 2000 and 1000 B.C.--had water supply and disposal systems, and they were skilled in the use of large masonry blocks which they placed in walls, buildings, and roads. From this point on the trail grows hazy once more, not to be picked up again until we come to the Hellenic Greeks.

Greek engineering drew its inspiration from the philosophers who began to flourish during the seventh and sixth centuries B.C.

with practical things. They considered mathematics a study of
in the Greek colonies of Asia Minor. First of the "schools"
of importance as far as engineering is concerned was that es-
tablished at the commercial city of Miletus. Here the names
of Thales (c 640-546 B.C.), Anaximander (c 611-547 B.C.), and
Anaximenes (fl. before 494 B.C.) stand out as originals in the
field of scientific speculation. Thales, who is probably best
remembered for having stated that everything is derived from
water, is reputed to have travelled to Egypt where he learned
mathematics. Though very little direct acquisition of know-
ledge can be traced to this source, it is probable that the in-
formation and ideas which Thales and those who followed him ac-
quired from alien lands aroused their interests in technical
matters. However, the importance of the Milesian school rests
not so much on what it achieved, but on what it attempted. The
Greek mind was brought into contact with Babylonia and Egypt,
and the vigor of the questions asked by these early philosophers
inspired subsequent investigators. Despite the early exchange
of ideas in many fields, however, there is little evidence that
Greek architecture--apart from the mathematics connected with
it--derived from Egypt or from any other earlier civilization.
The shaping of Greek thought continued in many "schools" subse-
quent to that of the Milesians, but it is not our purpose here
to discuss them. The important point to be gathered is that
groups of men sat down to think in a rational manner about tech-
nical and other matters; from thought came science, and following
on the heels of science came engineering.

The Greek philosophers are usually remembered as being in-
terested in knowledge for its own sake, abhorring any dealings

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with practical things. They considered mathematics a study of eternal things--ideas--and thus, as much superior to "applied mathematics" as is heaven to earth. Yet we count the philosophers among our early engineers. Witness the case of Archimedes of Syracuse (287-212 B.C.) who declined to describe on paper his "practical works because he considered such a course undignified, but who proved his willingness and ability to translate theory into practice at the defense of Syracuse (as noted above). Archimedes' greatest contribution to engineering lay not in his engines of war, however, but rather in the theoretical foundations he gave to hydrostatics and mechanics. The other great Greek contribution to engineering was also theoretical--the laying of the foundations of geometry. About 650 B.C. geometry consisted of a few rules of thumb, but by the time of Pythagoras (c 582-500 B.C.) it was becoming a theoretical science. It reached maturity with Euclid, whose "Elements" (c 300 B.C.) literally translated remained the standard textbook on the subject until the latter part of the nineteenth century. Euclid, who had a Platonian contempt for practical utility, probably never dreamed that some two thousand years later his work would provide a basis for much of the practical work of the engineers. The summing up and perfecting of geometry came during the Alexandrine period--a period which also saw great strides made in astronomy. Science at Alexandria, a commercial city, tended to be more practical than it was in Greece itself, and names like Ctesibius and Hero immediately turn our thoughts to mechanics and machines. Alexandria, which had been founded in 332 B.C., succeeded Athens as the philosophical center of the world, retaining this leadership from 300 B.C. to A.D. 300. However, the beginnings of scientific engineering which started there did not fully develop, and

after about A.D. 200 contributions from this source became purely scholarly. A slow decline set in and this seat of Greek learning finally died when the Arabs overran Egypt in A.D. 642. Greek science did continue in a fossilized state at Byzantium, though, until the Turks sacked the city in the fifteenth century.

Despite the eminent names we have connected with the engineering profession, we cannot say that as a group the Greeks were great engineers. They built few roads, bridges, tunnels, or canals, and they made no great contributions in the fields of water supply, irrigation, or harbor works. The mountainous character of their country undoubtedly contributed in a large measure to their relatively low output in this field. Small city states tended to remain in isolation, for extensive roads over the mountains would have been expensive affairs. For the most part, nature endowed Greece with a coastline of natural harbors, making extensive artificial harbor-works unnecessary. Mountain streams or springs were generally close to the city states they served, and thus elaborate water supply systems were likewise unnecessary. Because of the rugged terrain it was difficult to unite the country politically and economically, and without this unity great public works were impossible. Engineering is an economic as well as scientific achievement; to know how to accomplish a task is not enough, someone has to provide the money. In the case of the Greek city states, few were interested in contributing large sums to projects which did not directly concern their own city. What commercial intercourse there was could be carried on more economically by a few sea-going ships than by a vast network of roads with their necessary bridges and tunnels. There is no doubt that

the Greeks had the ability to construct great works where they felt that the result (usually more aesthetic than "practical") justified the cost. Evidence of this may still be seen in the remains of the Grecian temples which have won the praise of the architectural critics throughout the centuries. It was chiefly in this field of building construction that a Greek engineering tradition was passed on to the Roman world. Greek mathematics and astronomy, in the main, by-passed the Romans and were passed to Western Europe via the Arabs and Byzantine Greeks.

In summing up then, we may say that the main Greek contribution to civil engineering was theoretical rather than practical, for the Greeks developed mathematics and geometry which later became so important in engineering. This emphasis of theoretical over practical was due in part to the attitude of the philosophers who led Greek thought; it was due in greater measure to the country's geography--or to be more precise, its topography--which in turn shaped its political and economic life. The construction of vast public works, consistent with the technology of the times, could not be justified from an administrative or commercial standpoint, and so they were never brought into being.

With the emergence of Rome as the dominant power in the world, civil engineering reached a peak it did not again achieve until the nineteenth century. The Romans are not remembered, as are the Greeks, for their creative intellectual powers, but they are remembered as efficient organizers--soldiers, lawgivers, and engineers. Founded in the eighth century before the Christian era, Rome slowly grew in strength and influence until it dominated, in the time of Hadrian (second century A.D.), practically the

whole world bounded by the Mediterranean, the North Sea, the Atlantic, and the Caspian Sea. Many factors acted to hold this vast empire together, not the least of which were the Roman laws, the Roman legions, and the Roman roads. Road-building on a large scale was begun by the Romans in the latter part of the fourth century B.C., and it continued over the greater part of five centuries as the power of the State grew. The construction of these roads was such that their remains furnished the inspiration for a revival of road-building in seventeenth century France, and even today evidences of these old roads are still to be found.

The permanence and solidity which manifested itself in their roads was a characteristic which extended throughout all of their engineering endeavors. Aqueducts, bridges, tunnels, canals, and all forms of hydraulic works fell within the scope of the Roman engineers during the time of the republic and later under the emperors. In the first century A.D. the city of Rome had a public water supply system which furnished a per capita quantity of water equal to that of many modern European cities. The existing exposed aqueducts in various parts of what was once the Roman empire still excite wonder among people used to all the technical advances of modern civilization. Similarly many fine masonry bridges still stand, having weathered the onslaughts of nature for nearly two thousand years. Masonry theatres, temples, baths, and triumphal arches also remain--mute testimony that the Romans extended their constructive genius to every phase of their public and private life. The Italian coast is notoriously poor in natural harbors, but here again the Romans proved themselves equal to the challenge and produced the artificial harbors necessary

to maintain a fleet which regarded the Mediterranean as "Mare Nostrum."

In their construction practice the Romans inherited the semi-circular arch from the Etruscans and borrowed the post and lintel from the Greeks. According to the architect Vitruvius (first century B.C.) the Romans saw much that they liked in Greek construction methods and use of materials, and the Greek influence is readily seen in many of the large Roman buildings, from both the architectural and constructional viewpoint. Entirely Roman in character, however, was their fine natural cement which gave a monolithic character to much of their "concrete" and which was not duplicated in quality until the nineteenth century. Apart from this, they used the same materials which had been used by their predecessors, namely wood, stone, and brick.

Vitruvius and Frontinus, our two main Roman authorities on engineering, leave the impression that Roman Engineering was a highly developed rule-of-thumb "craftsman's" engineering rather than the more scientific art of today. Unfortunately no engineering computations have survived to permit us to determine how much of their work was guided by something which might be called science. In the Roman structures themselves we find definite evidence of the use of mathematics and geometry in their layout and construction. Closer inspection reveals that they were over-designed--by modern standards at least--a further indication that they were derived more from rule-of-thumb methods than from basic scientific principles. However, the modern engineer might slyly observe that they simply used a larger "safety factor" in those days.

Most of the public works were supervised and built by the state, slave and soldier labor being used extensively. The ultimate economy of that type of construction is open to question, but at the time it probably seemed an inexpensive method. It certainly encouraged a heavy type of construction which would have been too expensive for private enterprise. In their initial constructive efforts the Romans were not hindered by their topography as were the Greeks before them. Having built up their organizations on relatively easy terrain, the Romans were able to move to more difficult tasks gradually and in time to tackle the most difficult of problems. Thus, with initial topography and then organization in their favor, the Romans were able to rise to later topographical challenges which had kept the Greeks from ever getting started. The Romans were also challenged by new conditions, easy enough to master, which evoked further response from them. A case in point is the lack of natural harbors in Italy and the skill acquired by the Roman engineers in waterfront construction. Strong government and technological excellence went hand-in-hand; they were mutually helpful. As the boundaries of the empire were pushed outward, for example, the roads followed, and they, in turn, made efficient administration of the newly-won territories possible. After a period of consolidation the Romans were able to extend their boundaries once more. Engineering then, as Rome was on the ascendancy, was alternately an effect and cause of strong government. When the government began to break down, however, technology could not save it. The engineers did not at first lose their skill and know-how, they simply lost the funds to maintain the works they had built. Not only were they unable

to advance their techniques, they were unable--through lack of practice--to retain all that was best in their profession. Along with the other hall-marks of an advanced civilization, the art of civil engineering slowly died among the crumbling ruins of the Roman empire in the fifth century.

THE DARK AGES, THE MIDDLE AGES, AND THE RENAISSANCE

With the fall of the Hellenic civilization, knowledge reached a low ebb in the Western world, but it was not snuffed out altogether. A culture of mixed Greek, Roman, and Jewish origin survived at Byzantium and in the countries which stretch from Syria to the Persian Gulf. During the early part of the seventh century Muhammad (c 570-632) and his followers united Arabia and subjugated Persia, Syria, Iraq, and Egypt along with the northern coast of Africa, Armenia, and Asia Minor. Mu'awiya, first of the dynasty of the Umayyads, became sole ruler of Islam in 661 on the death of the caliph 'Ali, Muhammad's cousin and son-in-law, and in his capital at Damascus the learning which had been preserved by the Nestorian Christians and other conquered groups slowly rose to the surface. A further and greater impetus to learning was given by the 'Abbāsides who replaced the Umayyads in 750. The capital was then moved to Bagdad which shared the distinction with Alexandria and Andalusia of being a great center of learning in the Arab world. From the latter part of the eighth century until the twelfth, the Arabian schools made important contributions in the fields of mathematics, astronomy, physics, and medicine. Generally speaking, these contributions were not in

the nature of new discoveries but were rather the collecting and preserving of the knowledge of previous civilizations. Isolated instances of civil engineering appear in the Moslem world of this period, but apart from studies skin to surveying, they seem to bear little relation to subsequent development in this field. Finally the great period of Arabic learning was brought to an end by a fanatic Islamic priesthood in the twelfth century. The importance of the Arabic civilization rests in the fact that it served as the "funnel" into which the knowledge of Greece, the Near East, and to some extent India and even China passed. Here it was absorbed and passed on to the Western world of the Middle Ages.

The withdrawal of the Roman legions from Western Europe marked not only the end of a stable political organization in that sphere, but it also ushered in an age of ignorance which lasted for centuries. Only in the Church did a strong organization survive, and it was the Church also which kept a flicker of learning alive in a continent dominated by semi-barbaric Germanic tribes. Probably the last to show the true spirit of ancient philosophy was the noble Roman Christian Boethius (c 420-524) who wrote compendiums and commentaries on Plato and Aristotle. His works, together with those of Cassiodorus (490-580) and Isidore of Seville (c 560-636), formed an important link between the Classicists and the Medievalists. Public works came to a complete halt as old Roman roads, bridges, and aqueducts slowly fell into decay. Only under Charlemagne (742-814) was any concerted attempt made to revive the art of civil engineering, but it withered away soon after his death. What scholarship there was devoted

itself more to mystical philosophies and to religion than to practical mechanical arts. Nevertheless, it was the medieval monastery which led the way to a revival in engineering. In the twelfth century we find pious monks in Italy, France, and England taking up the task of building bridges and other works modeled after Roman remains. Monastery water supply and drainage systems also began to appear about this time, as did the great Gothic cathedrals which still excite our admiration. Master craftsmen, guided more by experience and tradition than by scientific principles, were the architects and engineers of these great works. The later Middle Ages were also marked by the construction of irrigation and drainage canals in both Holland and Italy, and for generations Dutch and Italian engineers were regarded as supreme in all types of hydraulic work. In time the ecclesiastics passed their knowledge and skills to the laity in the great period of enlightenment which followed. Here and there Europe was prepared for the new learning which percolated in from the Arabic world. By the latter half of the twelfth century the schools made up of collections of students and masters began to take their modern form of Universities at places such as Bologna, Salerno, Paris, and Oxford. To be sure, the nature of the subjects studied bore little relation to engineering--except possibly in the field of mathematics--but the questions asked represented a new interest in learning. Even the mathematics were of little use to the engineer of the time; their value to the engineering profession was not to be realized until a later age. An increasing desire for secular knowledge led to the translation of many old works from Greek

to the Latin. Often, of course, the texts suffered in translation which might, for example, go from Greek to Syriac, Syriac to Arabic, Arabic to Spanish, and Spanish to Latin. The effect of this new knowledge was to further stimulate thought and discussion. Mystical Neo-Platonism, which had come to represent ancient philosophy, gave way to the more rational and more scientific outlook of Aristotle, and Aristotle's science and Christian doctrine were combined by St. Thomas Aquinas (1225-74) in the system which came to be known as Scholasticism. The whole of the Thomist philosophy was founded and built up on reason, and sought to explain God and natural phenomena in this light. Friar Francis Bacon (c 1214-94) urged that reason alone was not sufficient and that observation and experiment were needed in the interpretation of nature. In addition to experiment, Bacon valued the use of mathematics, but he was three centuries ahead of his time in this respect and gathered no great following among the Medievalists.

Throughout the medieval period the laity bowed to the ecclesiastics in most matters, for the established religion was thought to have the ability to decide--on the authority of Scripture and Tradition--not only questions of theology and morality but even some matters of scientific interest as well. In the fourteenth century, however, the Papacy and a rich Mediterranean trade brought forth a monied and leisure class in Italy which began to look beyond the confines of its narrow mental prison. Interest in the Classical world was intensified, partly because the Roman remains were everywhere in evidence to excite curiosity, partly because further commercial interests

start by experiment and end with conclusions.

remembered among engineers for his contributions brought people together in towns, and partly because Italian especially in the field of naval architecture and shipbuilding traders formed a contact with the older civilizations of the East. Greek scholars, fleeing before the Turkish horde which sacked Constantinople in 1453, gave a fresh impetus to the study of engineering and mathematics in the West, and the perfection of the art of printing at about this time helped to diffuse the new knowledge. Thus, during the fifteenth century the cult of the classics became almost a passion among the ruling and merchant class. The influential merchant class soon perceived, however, that the answers to all of its "practical" questions could not be found in the works of the ancients, the Arabs, or the scholastics. Once more a fresh approach to knowledge was clearly in order.

Except in the field of architecture and building construction, the Renaissance was more a time of ideas than of action insofar as it affected the engineering profession. Most of the construction of the period was that done by military engineers in the employ of some duke or prince. Fortifications and artillery, the main interests of the engineer in the early Middle Ages, still occupied the bulk of the engineer's time. In some cases, however, the engineer was more than just a constructor of fortifications; he was--for want of a more descriptive term--a "Renaissance Man," a man who knew practically everything there was to know in his day. Such was Leonardo da Vinci (1452-1519), architect, biologist, engineer, painter, philosopher, and sculptor, who lived successively in the courts of Florence, Milan, and Rome, and died in France, a friend and servant of Francis I. He rejected reliance on authority in favor of seeing for oneself, and he was among the first to urge that scientific work must start by experiment and end with conclusions. He is particularly

remembered among engineers for his contributions to hydraulics, especially in the field of canal and lock construction. However, he left no published writings (although his "Notes" were subsequently put in book form) and so his influence on the progress of engineering was comparatively small.

Mathematics and astronomy went forward with the times. Fifteenth and sixteenth century astronomers Purbach, Regiomontanus, Copernicus, and Tycho Brahe all made significant contributions which were felt in navigation and subsequently in surveying and cartography. Geometry from the Greeks was firmly established and algebra, introduced by the Arabs, was gradually taking hold. These two subjects also entered engineering via surveying but were not generally employed elsewhere in the profession until the nineteenth century. Pioneering work in statics was begun in the latter part of the sixteenth century by the Dutchman Simon Stevin, and important studies of the magnet were made by William Gilbert of Colchester during the same period. Until about 1600 we find a gradual accumulation of knowledge with little attempt to systematize it in any order and very little attempt to adapt it to practical use. The seventeenth century witnessed not only a continuation of the harvesting of facts, but it also saw the rise of experimental science. Francis Bacon, Lord Verulam (1561-1626) recognized the value of extensive experimentation, but he found difficulty in selecting the right experiments to indicate the answers to his questions. His main contribution lies in the fact that he reversed the view of Archimedes--who felt that practical devices should remain unrecorded--by setting up as a lofty object the making of scientific devices for man's practical use.

Throughout the seventeenth century men continued to lay solid foundations for sciences which would soon blossom forth in terms of practical application. Probably the man who contributed most in starting science on its triumphant course was the Italian Galileo Galilei (1564-1642) who, in his work on dynamics and statics, combined observation and induction with mathematical deduction tested by experiment, and thus ushered in the true method of physical research. The century was marked by the contributions of some of the brightest names in science, namely Gilbert, Kepler, Hooke, Torricelli, Pascal, Boyle, Huygens, and Newton. The last, Sir Isaac Newton (1642-1727), exerted the widest and most profound influence. His "Philosophiae Naturalis Principia Mathematica" published in 1687, has been considered by many the greatest book in the history of science. His concepts of force, momentum, acceleration, etc. provided an excellent starting ground for the engineers who began to translate theory into practice in the latter part of the eighteenth century.

One of the chief advances of the seventeenth century was the formation and growth of scientific societies. The first such society to be formed was the "Accademia Secretorum Naturae" at Naples in 1560, and it was followed by two other Italian bodies, the Accademia dei Lincei (1603) and the Accademia del Cimento (1657) of Florence. The next body of importance to be formed was the Royal Society which was given a charter at London by Charles II in 1662, and four years later Louis XIV gave official recognition to the Académie des Sciences at Paris. Lagging somewhat behind was the Berlin Academy which did not receive its charter until 1700. In the early years those

societies gave scant consideration to civil engineering, but towards the latter part of the eighteenth century the relation of engineering to science came to be more and more recognized by the societies, especially in England. Also of great importance during the seventeenth century were the various inventions which made the measurement of length and time exceedingly more accurate than had ever been possible before. This advance was, in turn, reflected in improved surveying and better maps.

THE RISE OF THE ENGINEERS -- THE 18th CENTURY

Though the seventeenth century is looked upon chiefly as a period of scientific speculation, it also marks the early beginnings of modern civil engineering in France. It was during this century that the old Roman roads were unearthed, a discovery which had far-reaching effects in the development of the road in France. Even more important was the rise of the barge canal, encouraged by the ministers Sully, Richelieu, and Colbert. Again it was a strong government seeking to increase its strength by means of public works which pushed these lines of transportation rapidly across the country. As the seventeenth century drew to a close, it was evident that the foundations were in the making for what subsequently proved to be the great engineering tradition of the French.

Recognition of the need for trained civil engineers was signalized in France by the opening in 1760 of the first engineering school in the world, the *École des Ponts et Chaussées*. The school was the outgrowth of earlier institutions which

dated back to the founding of the Corps des Ponts et Chaussées at Paris in 1716. Here for the first time was a systematic attempt made to derive empirical data from past construction work in order to build future structures more efficiently. Essentially, of course, engineers had always built in this manner, but heretofore the empirical information was stored in men's heads and little effort was made to arrange it scientifically. Thus the habit of experimenting, thinking, and drawing conclusions as practiced by the seventeenth century philosophers and scientists began to bear fruit in the practical world. The Corps concentrated its efforts mainly on masonry bridges and permanent roads. Before the century was out the French bridges were unexcelled anywhere in the world and the French roads had reached their highest peak of development since the time of the Romans. The eighteenth century in France also saw a continuation of the work of the brilliant French mathematicians who laid much of the theoretical groundwork in mechanics and hydraulics. Mariotte and James Bernoulli of the seventeenth century were ably followed by Daniel Bernoulli, Parent, Coulomb, and Girard of the eighteenth. Across the channel in England a new class of engineers also began to rise in the eighteenth century, but they differed somewhat from their theoretically trained French counterparts. For the most part, the early English engineers were blacksmiths, wheelwrights, masons, and the like, definitely "practical" men and largely self-educated in the field of scientific principles. Generally speaking, these men progressed empirically, and scientific principles followed rather than led their inventions. In a few cases, of course, they were men of science in addition to

being men of "practical" outlook. Most noteworthy in this class were Smeaton and Watt, who proceeded from scientific principles to practical achievement and vice versa. The most important of the practical inventions of the century was the steam engine, first put in a usable form for pumping water by Savery in 1698 and shortly thereafter improved by Newcomen. Its early use was confined almost exclusively to the pumping out of mines, but when James Watt made it into a machine of reasonable efficiency in the last quarter of the century a whole new world of power was opened. Up to this time the English textile industry had found its rate of spinning hampered for want of a more efficient prime mover than the water wheel. Merchants and traders were in the position of being able to sell their products more rapidly than ^{they} ~~it~~ could be manufactured, for Britain's command of the seas had brought her immense overseas markets which clamored for English manufactured goods. With the introduction of Watt's engine the old "mills" were soon converted to steam, and new factories sprang up in places formerly by-passed because of their lack of quickly moving streams. The total effect was to increase production and to accelerate the movement of workers from their individual spinning wheels at home to those at the factory. The whole thing was like a snow ball rolling down hill; factory sites became towns and towns grew into cities, a factor which brought new calls on the engineer.

The rise of industrialism brought a new point to light-- transportation was hopelessly inadequate. The problem was solved initially by the introduction of canals. Englishmen had long been accustomed to using their navigable rivers for trade, so

it was not an entirely novel idea that they should resort to canals to move both raw materials and the newly manufactured goods. When it was found that a canal could be a commercially sound investment, the rising industrial class proved full of ready backers, and from about 1760 to 1830 the canal reigned supreme in the transportation field in Britain. Topography and climate proved favorable for this type of construction, and it was in this field that most of the early civil engineers received their initial instruction. The very nature of the work gave them not only a good background in cutting canals and in erecting waterfront structures, but it also stimulated the construction of bridges, aqueducts, and tunnels. It was a training designed to stand the profession in good stead as increasing demands were placed upon it in the nineteenth century. The demand for better transportation was also reflected in the emergence of the turnpike roads. Like the canals they were the product of private enterprise, but unlike the canals they received little praise during the eighteenth century: indeed, most of them deserved all of the verbal abuse they got. Little attempt was made on the part of turnpike trusts to secure the services of competent engineers to direct the construction of these roads, and the results showed it. No real progress was made until the early nineteenth century when John M'Adam introduced the relatively inexpensive broken stone road. His method rapidly found favor in Britain and soon became popular all over the world.

Though the eighteenth century looks rather barren of scientific achievement when compared with the century which preceded

(and followed) it, the same cannot be said of engineering. In France and in England--the main centers of engineering activity in this period--the scientific men faded somewhat into the background but the practical men came to the fore. Not only did a class of "civil" engineers as distinct from "military" engineers arise, but even in the army the duties of engineers became more sharply defined. The Corps de Genie, founded in 1690 by Vauban, merged with the artillery in 1755 for a time, but it soon confined its functions to engineering as we now know it. After the rebellion of 1715 the artillery and engineers of Britain were separated by royal warrant (1716), but they remained for a time loosely joined together under the Board of Ordnance. In the United States artillerists and engineers were grouped together in 1794 and were separated in 1802 when the Corps of Engineers was organized at West Point. Military and civilian engineers alike turned their attention towards roads, bridges, and harbor works during this period with a vigor unknown since Classical times. Impressive though these beginnings were, they were but the first trickle of what was to become a flood of technology in the nineteenth century.

MODERN CIVIL ENGINEERING

The point at which civil engineering entered the "modern" stage is, of course, an arbitrary one, for no clear-cut line can be drawn separating the old from the new. Perhaps our best course is to observe when civil engineers themselves decided that their calling was noble enough to warrant recognition as

a profession. This decision was represented, in the main, by the formation of the professional societies which came into being in many countries throughout the course of the nineteenth century. First of these was Great Britain's Institution of Civil Engineers, established in 1818 and incorporated in 1828. Prominent among those which followed the British lead were the Maatschappij ter Bevordering der Bouwkunst (1843) of Holland, the Association des Ingénieurs (1847) of Belgium, the Société des Ingénieurs Civils (1848) of France, the American Society of Civil Engineers (1857) of the United States, the Ver. Deutscher Ingenieure (1857) of Germany and Austria-Hungary, and the Società degli Ingegneri (1868-70) of Italy. The same period saw the rise of the technical school--the engineering college--which was to play such a large part in fusing the artisan and the scientist into a new product, the modern engineer. In Europe the instruction was largely carried out under government bureaus as in the case of the École des Ponts et Chaussées, or under professional engineers as in the case of the "Mechanics Institute," founded in 1823 by George Birkbeck at Glasgow and London. In the United States the task fell largely to professional educators and educational scientists. The first truly civilian technical school in America was the one founded at Bowdoin College, Maine, by Benjamin Hale in 1822, but it lasted only ten years. Two years after Hale's start Stephen Van Rensselaer founded a school at Troy, New York, for teaching "the sons and daughters of farmers and mechanics" the application of science to "agriculture, domestic economy, the arts and manufactures." General engineering soon entered the curriculum,

followed by civil engineering in 1829. This college along with West Point then furnished all the native scientifically trained engineers in the country until the middle of the century. Encouraged by their government, French engineers of the eighteenth century had reached a peak of achievement in their profession unrivalled by that of any other nation. A combination of factors which included British sea power, the invention of the spinning jenny, and the invention of the steam engine acted to bring engineers in Britain along rapidly during this time so that as the nineteenth century dawned, the superiority held by the French passed to the British. The history of the early years of modern civil engineering--as we have defined it--is, therefore, largely a history of the accomplishments in Britain. It starts with Thomas Telford (1757-1834), first president of the Institution of Civil Engineers. Like most of the engineers of the day his formal education was slight, and he began work at an early age as a mason's apprentice. Through innate intelligence and diligent self-education Telford raised himself to a position where he was regarded as the most eminent civil engineer of his time. His influence was felt in every part of Britain and in many continental countries as well, for he designed and supervised the construction of numerous roads, bridges, buildings, canals, tunnels, drainage systems, and harbors. In fact, he engaged in every type of construction known to the civil engineer of the time with the exception of railroads, and he was well past his prime when they began to emerge. His name survives in a type of road construction and his statue stands

in Westminster Abbey, but his memory is even better served by a living organization which points with pride to him as its first head. No man was more eminently qualified than he to lead civil engineering in its first official footsteps from the realm of a skilled trade to the full dignity of a respected profession.

In Telford's declining years the steam engine, which was rapidly bringing about a revolution in industry, extended its influence to ^{the} transportation field. Horse-drawn railways had long been known in mining circles, but the introduction of the steam locomotive suggested to men of vision the practicability of a transportation service never before dreamed of, and George Stephenson's "Rocket" showed in the Rainhill Trials of 1829 that the steam locomotive was now ready to take its place in the commercial world. The opening of the Liverpool and Manchester railway in the following year signalled the beginning of the Railway Age. The same factors which had acted to popularize canals almost a century before--climate, topography, wealth, technical ability, and commercial incentive--again came into play. Canals had been satisfactory in their time, but the flood of goods which began to move in the early nineteenth century practically overwhelmed them. Lack of centralized control in the early building period had resulted in canals of varying size being linked together. This lack of uniform scale meant naturally that a maximum efficiency in barge size and loading could seldom be achieved. It was only one of many factors which played a part in sounding the death knell of the canals as railroads gradually overtook and all but eliminated them. Probably its greatest importance lay in the fact that it served as a valuable lesson to the

builders of the railroads when the problem of one or many gauges had to be faced. The outcome, of course, was the adoption of a standard gauge on English main lines--a gauge which was subsequently adopted on a majority of main lines throughout the world.

Not only did the railroad change the face of the countryside, it materially affected the progress of civil engineering as well. The art of tunneling advanced once more, as it had during the canal boom. Drilling and blasting techniques were improved and the tunnel shield appeared. Engineers began to burrow under rivers and under cities already built in order to permit their trains to reach ever increasing markets. With the development of the subaqueous tunnel came the use of compressed air and a knowledge of how to use it safely. This knowledge was, in turn, incorporated in foundation work, especially in the case of bridge piers. Here more knowledge and experience was accumulated and returned again to the tunnel men. The increasing train loads also brought about a change in the design of bridge superstructures. Hitherto masonry arch bridges had stood for centuries, capable of withstanding the normal punishment of man and nature. They continued in use in the early days of the railroad, but it soon became apparent that masonry construction would reach its economic limit long before that condition was reached by the track, locomotive, or other rolling stock. Clearly some new material or some new principle of design, or both, was needed in the railway bridge.

Iron boilers for the locomotives and iron rails for the tracks--it was only a matter of time before iron bridges would take their place alongside of the other pieces of iron equipment

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on the railroads. The manufacture of cast and wrought iron had been slowly improving throughout the eighteenth century, and demand increased with the years. Despite this improvement, a combination of quality and quantity was lacking until the latter half of the nineteenth century when Bessemer and Siemens-Martin steels came on the market. Some iron railroad bridges were constructed during the first half of the century but they were for the most part, modest pioneering efforts, noted neither for their structural nor their aesthetic qualities. Of special significance was the development of the bridge in America at this time. Vast quantities of timber readily at hand made the development of timber framed structures only natural here, with the result that a new structural type, the truss, was popularized and perfected. Slowly iron began to replace timber in the truss until at last (1845) the all-iron truss railroad bridge was a reality. The challenge provoked by the railroad had been answered by the production of a bridge which combined both a new material and a new principle of design.

Tunnel and bridge construction were but two of the many sections of civil engineering tremendously influenced by cast iron and the steam engine early in the nineteenth century. The increase in trade and industrialization brought an increase in towns and an increase of populations, thus rendering obsolete the older systems of water supply designed for relatively small numbers. A solution to the pumping problem was found by the introduction of the steam engine, but this in turn raised the question of where to get a suitable pipe which could contain the high heads produced by the new machine. Cast iron, which

had made the steam pump possible, once more proved itself the answer. No sooner had the method of supplying an adequate amount of water to a large community been established, however, than a further problem--that of a pure supply--arose. Initially, before the germ theory of disease came to be generally accepted, water treatment was designed simply to improve clarity, taste, and odor. As with most other significant advances in civil engineering of the period, the first full-scale filtration of a municipal supply was carried out in Britain in 1829.

As had been the case before, however, solution of one problem merely brought others to the fore. Supplying and clarifying the water was only half the job, getting rid of it after it had been used was the other. Haphazard drainage systems had seemed sufficient when towns were small and where privy-middens could be used almost exclusively for waste without undue annoyance, but the rapid expansion of the towns in England in the nineteenth century was accompanied by intolerable sanitary conditions which could not be overlooked by social reformers, doctors, or engineers. The 1844 Report of the Commission on the Health of Towns shocked the nation into activity, and resulted in the gradual adoption of the water carriage system of sewage disposal. In most cases the raw sewage was simply carried to the nearest stream or body of water and dumped. Here again a new problem was created, for the pollution of rivers and streams was accelerated as a result and potable water supplies were threatened. This called for renewed efforts in the field of water treatment and a newer approach to the sewage disposal problem in the latter half of the century.

Most solutions to previous problems coming under the scope of the engineer had been found by the further application and extension of engineering principles, but the water supply and sewage disposal questions were found to have other roots in the fields of medicine, chemistry, and bacteriology. Many of the same factors which had been responsible for the advancement of engineering techniques acted on these fields, and now all were joined on common ground. The contributions of Pasteur, Koch, and others in showing how diseases could be transmitted, threw a new light on the whole matter and led to an increased appreciation of the necessity for adequate and safe supply and disposal systems. Experiments on water treatment and sewage disposal proceeded side by side, with the result that an advance in one field became an advance in the other. The latter part of the century witnessed extensive trials with chemicals and with various types of filters, and by the end of the century the basic problem of providing proper sanitary facilities for large populations had been solved.

A great part of England's expanding prosperity during the nineteenth century was due to her supremacy of the seas. In the final analysis, a fleet--if it is to remain powerful--must have excellent shore facilities to service it. Thus the civil engineer was identified with yet another phase of material progress, for he was called upon to erect the harbors and docks and all manner of waterfront works to service this ever-growing fleet of merchantmen. The introduction of steam in place of sail gradually brought about the construction of larger vessels, and this in turn meant greater improvement to waterfront structures.

Experience gained in this type of work combined with that of drainage, irrigation, water supply, and sewerage brought forth the same sort of interchange of ideas with mutual benefits resulting as had been the case in so many other phases of engineering progress. With his increased hydraulic skill the civil engineer was ready to take on the job of building the large ship canal--as exemplified by that at Suez (1869)--when increased trade and the steamship made such a venture worth while.

Thus far we have considered primarily the rise of modern--i.e. nineteenth century--civil engineering in Great Britain, but the story is roughly the same in other countries. The Industrial Revolution took place in England first, so it was natural that the early developments in civil engineering should also have their home there. Countries whose industrialization closely followed that of Britain found themselves with problems very similar to those of the English and their methods of solution and their mistakes generally followed the English pattern. Those countries whose industrialization lagged behind Britain's a great deal did not make--or have to make--the same mistakes but were able to profit by the experience of those who preceded them. Particularly was this true in the case of town planning. Some cities in the eastern United States show the same lack of planning for future growth that is exhibited in many of the early industrial cities of Britain--both having begun to grow about the same time--but most of the cities in the western United States, which developed at a later date, show some thought in their lay-out. Although town planning is older than Vitruvius, it seems to have been generally overlooked by most engineers, except those of France

in the heyday of nineteenth century construction, and it is not until the twentieth century that we find wide-spread attention devoted to the subject.

Until the nineteenth century the civil engineer was limited in his choice of building materials to stone, brick, or timber--the same materials which had been in use for centuries. By this time he had brought their use close to the economic and aesthetic limits, meaning that further progress would be dependent on the introduction of new materials. Those new materials appeared in the form of Portland cement concrete and steel. Portland cement was introduced in Britain in 1825, but decades passed before Portland cement concrete reached a popular stage. Steel, on the other hand, was adapted to almost every conceivable use soon after Bessemer announced the discovery of his converter in 1856. Its effect was felt in every branch of construction: longer bridges, taller buildings, greater floating drydocks, heavier trains, and stronger construction equipment were all made possible now that great quantities of steel could be produced economically. Adding iron or steel bars to concrete to obtain reinforced concrete also began in the latter half of the century, but it was not until the twentieth century that this material gained the confidence of most builders.

A quick glance at the growth of civil engineering in the nineteenth century reveals certain obvious factors which affected it such as the inventions of new machines and the introduction of new materials, but closer scrutiny will show an equally important--though more subtle--factor, the influence of thought and education. We have previously noted the growth of thought which culminated in

the brilliant scientific discoveries of the seventeenth century. Eighteenth century thinkers turned their questions more to politics and economics and discoursed at length on the dignity and rights of man. This thought pattern carried over into the nineteenth century in the form of practical Christian societies devoted to the principle of raising the standards of living of the underprivileged. In heeding the demands of these groups, society called on the engineer to use his ingenuity and skill to bring about material improvements for this purpose. Thus, the engineering profession was affected directly by the wave of humanitarianism (and commercialism) which began to sweep over the Western world at this time. Indirectly the profession was affected even more. One result of the reform was the establishment of a greater number of regular educational institutions than had ever been known before. Education was no longer for the rich and privileged alone, it was rapidly coming to be regarded as a birthright of the common man. Accordingly, more people took an active interest in the ever-increasing fields of knowledge opening up on all sides. Slowly, isolated scientific bits of knowledge came to be fitted together and re-examined in relation to the whole of the physical world. Mathematics moved rapidly from the realm of abstract theory to that of practical application, and the study of the strength of materials increased in importance proportionally. Almost imperceptibly theory and engineering practice were drawn closer and closer together, until finally the two were inseparable. The uniting of the two was pointed out by Maquorn Rankine in "The Harmony between Theory and Practice in the Science of Engineering," an address he delivered upon

being appointed to the Chair of Engineering at Glasgow University in 1855. In place of the theorist of the seventeenth century and the "practical" man of the eighteenth century stood a new figure of the nineteenth century, the engineer--scientifically trained to accomplish practical ends.

This brings us to the question of just when the engineer ceased to work by rule of thumb and was able to predict and plan his results by the use of scientific laws and mathematical reasoning. Strictly speaking, rule of thumb has not yet disappeared from engineering as every engineer knows. The designer who adds on that safety factor and the construction superintendent who adds a little more water to the concrete mix merely affirms that engineering has not yet completely passed to the realm of science but still remains something of an art. Nevertheless, no modern engineer will build a work of any appreciable size without a set of plans which are derived from scientific laws and mathematical reasoning. What we really must decide then, is when the emphasis in engineering design shifted from calculations based on rule of thumb to those based on truly scientific principles.

Actually, the time when this shift in emphasis became significant did not coincide with the beginning--as we have defined it--of modern civil engineering. We have previously associated the beginning of modern civil engineering with the name of Telford and with the incorporation of Great Britain's Institution of Civil Engineers in 1828--the time when civil engineering came to be formally recognized as a profession both by its members and by the outside world. At the time of its recognition as a profession, engineering still had most of its roots of design in

"practical" rather than in scientific principles. By the middle of the nineteenth century, however, the shift to the scientific emphasis in design had become apparent. Two works, one American and the other French, stand out above the rest in ushering in this new era in engineering. Squire Whipple's first treatise on stresses in trusses (1847) and De Sazilly's analysis of dam design (1853) marked the beginning of truly rational and scientific design in civil engineering. From this time forward design passed out of the hands of the "practical" men into the hands of those with scientific training, and progress in the profession leaped forward at an astounding pace during the latter half of the nineteenth century.

Notable as were the engineering accomplishments and changes in the nineteenth century, they were but a prelude to the wonders which were to be wrought in the twentieth. Concrete and steel construction climbed from the initial clumsy and halting efforts to a maturity characterized by economy and beauty. The growing tempo of city life demanded more and better services in transportation, public health, and commercial and private structures. Larger flood control projects, bigger dams, and more complex power houses were the civil engineer's contribution as electricity became more a part of every-day life. The emergence of the automobile, however, provoked the biggest response of all from civil engineering. Its introduction was to the twentieth century what the railroad had been to the nineteenth and the canal to the eighteenth. The old system of road-making was out; new materials and new techniques were needed to cope with this latest vehicle to take the road. Not only were roads affected, but bridge and tunnel design came in for radical revision.

New designs for lighter loads meant further experimenting with hitherto unsatisfactory or undiscovered materials.

The influence of the automobile and the road on the lives of ordinary citizens has been tremendous. Like the railroad, subway, and tram-car it has enabled people to live at some distance from their work and yet commute comfortably each day. As a result, cities have gradually spread out as successive waves of fugitives from the factories have settled down in relatively uncongested residential suburban areas. Fresh farm produce, brought long distances from the country, has become normal fare for the average city-dweller, and few think it extraordinary to travel miles for a simple day's outing. It is clear from just these few examples that a profound change has been brought about in a half a century in the lives and habits of the people served by these means of transport. Small wonder that our Air Age enthusiasts predict sweeping changes in the world of the future! Here again the civil engineer is primarily concerned, for his is the responsibility for designing and building the runways and airports. Clearly the profession has continued to move with the times, for in every age the civil engineer has been involved wherever any carrier has touched solid ground.

Facilitating every type of transport, be it on or in the land, sea, or air, has always been one of the primary functions of civil engineering throughout its long history. The influence of transport in shaping the political and economic world has been, of course, so great as to almost defy description. Without roads or harbors or airports and the appropriate carriers to use them, civilization--as known by the Western world--would soon vanish.

The movement of raw materials to the factories would be cut off, industry would stop, trade would die, city populations would starve, governments would fall, and anarchy would reign. True, nations would lose their ability to wage war on one another, but then nations as such would soon cease to exist. The clock would be turned back six thousand years as man returned to the primitive state. Perhaps this picture is somewhat overdrawn, but it does serve to dramatize the contribution of the civil engineer in the shaping of the modern world. In a similar vein we can well imagine the fate of cities were they deprived of the water supply and sewerage systems which have made their safe growth possible. And who will deny the advantages to mankind derived from the drainage and irrigation of countless acres of formerly worthless land?

Briefly then, we have noted the influence of the civil engineer on his environment, but there is a further point to be considered--the influence of the environment on the civil engineer. In every case of outstanding engineering achievement the same factors have been in evidence. First of all, topography has been favorable in initial instances, tough enough to evoke a response, but gentle enough to be overcome. Aided by their increased confidence and guided by their past experience, engineers from a country with such topography have been able to go into areas of increasing topographical difficulty and master conditions which would have been impossible to master had they attempted to lay the foundations of their skill there. The effect of climate has been similar. Practically all engineering knowledge has originated with people from temperate

climates who have neither been all but overwhelmed by arctic blasts nor enervated by tropic heat. Another decisive factor has been wealth, both in the form of workable materials and in the form of financial backing. The first depends on nature, but the second may stem from government or private enterprise. Regardless of the source of the financial backing, however, government must be regarded as another factor, for only under relatively stable political organizations has true engineering progress been made. Commercial benefits have provided much of the incentive in engineering, but a great measure of credit must also be given to those men of public spirit who have, with no thought of financial gain, labored to make this a better world in which to live. The combination of all these factors has encouraged engineering development where the seed of rational thought has been firmly planted. From thought has come knowledge, and from knowledge, power--power of man over his environment. In the final analysis, the effect of the engineer on his environment and the effect of the environment on the engineer cannot be separated. One has continually acted and reacted on the other until cause and effect are hopelessly intermingled. One fact emerges clear, however; the engineer has played a leading role not only in changing the face of the earth but in shaping the destiny of nations and of men as well.

Let us now turn to a more detailed account of the various works of civil engineering which have brought about such a change in our world.

FOOTNOTES

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Chapter II

MATERIALS AND BUILDING INDUSTRY

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timber, however, the climate of the Nile has preserved many pieces of wood which were worked by the Egyptians, indicating that they possessed a skill

PRIMITIVE DWELLINGS -- The first type of construction used by man to shelter him from the elements will always remain a matter of speculation, for evidences of such a flimsy structure, as it must have been, have long since vanished. It is very likely that once he had moved from his shelter provided by nature the primitive dweller--influenced by the climate--built a cave in imitation of natural caverns or a shelter of twigs and mud in imitation of the birds. Huts made of forked sticks connected by interwoven twigs and covered with mud were soon joined by those made of lumps of dry mud covered with reeds and leaves. Having succeeded in his primary object of providing shelter, the builder's next concern was to make his protection more efficient. Thus appeared the sloping roof, peaked with mud, to carry off the rain. As materials more durable than twigs and mud were discovered, the art of building progressed; huts became houses, temples and palaces appeared, and man passed from the barbarous to the civilized state.

PRE-GOTHIC USE OF TIMBER -- Owing to the perishable qualities of timber, we have very few examples of its use in building construction prior to Gothic times. It was, of course, one of the earliest materials used by the Egyptians, although its shortage in that land relegated it to a relatively minor role. That a certain measure of importance was attached to working with

timber, however, might be inferred from the fact that the master of the works was often styled the "royal axe-man." The climate of the Nile has preserved many early pieces of wood which were worked by the Egyptians, indicating that they possessed a skill in joinery which was not exceeded in England until the fourteenth or fifteenth century. They knew dovetailing, mortising and tenoning, halving, bevelled halving, mitreing, and housing. One fine example of their art is the wooded statue of Sheykh el-beled, nearly five thousand years old, which stands in the Cairo Museum. Unfortunately, from the standpoint of this study, most of the pieces discovered thus far have been more in the field of art than in the field of building construction. We do have examples, though, which show that they used timber in the construction of floors and flat roofs. Planking 2 or 2½ inches thick was fastened to beams 7 by 10 inches and more, and some royal tombs had beams 10 inches square and 18 to 20 feet long.

We know little of the early use of timber in Assyria, apart from the fact that a general use was made of palm trunks, and that cedar beams were used for the ceilings of palaces. In pre-Hellenic Greece shipbuilding seems to have claimed most of the wood. Almost all of our knowledge of this period is confined to the rock-cut tombs of Lycia in which timber forms have been reproduced in stone. Later Greek work is known to us only through a few meager written descriptions. During Roman times timber must have occupied a very important place among building materials, if we may judge from the writings of Vitruvius. In his "Ten Books on Architecture" he devoted several pages to timber, its kinds, quality, where found, and the like. The best types

for building he considered to be elm, poplar, cypress, fir, and oak, though he did not seem to be too favorably disposed towards oak. While he mentioned parts of a roof, the evidence of the practical details is not clear, and no original Roman building in wood has yet been discovered to clarify the situation. Wooden roofs were used by the Romans mainly for the early temples and later basilicas, but the great thermae of the middle period were roofed in "concrete." In the large wooden-roofed buildings fireproofing was accomplished by carrying up the stone walls between portions of the roofs.

Again little is known of timber roof construction in Byzantine architecture except that wooden tie beams were used largely to resist earthquake shocks. In the Arab world the Saracens in Egypt encountered the same scarcity of timber experienced when the Pharaohs had ruled the land. During the seventh century A.D. the Arabs imported woods from India to Mecca and from Cyprus to Jerusalem, and in later years oak and pine came to Cairo from Turkey. Wooden tie beams were largely employed in the arcades of their mosques and flat timber roofs were not uncommon. One fine example of their use of timber still exists in Cairo--the ninth century mosque of Ibn Tulun. Its flat roof of earth, lime, and slabs rests on sycamore planks supported by heavy beams carried on corbels, and the heavy doors of this structure have been pivoted on wooden pegs 3 inches in diameter.

As they had in Byzantine times, wooden tie beams appeared in western Europe once more during the Romanesque period. Especially was this true in construction where the walls carried barrel vaults imbedded at the springing level. Very often the

craftsmen of the time employed arches where modern constructors would erect roof trusses. The upper rubble surface of early vaulting was often protected by rafters supported at their centers on the back of the vaulting. This style gradually gave way to plain and simple tie-beam roofs and prepared the way for the more elaborate Gothic roof structures of the Middle Ages. The flat Roman pitch was gradually increased to meet the climatic conditions, but it never exceeded 45 degrees.

FROM MEDIEVAL TO MODERN TIMES -- As the Gothic style of architecture spread across Europe steeper roofs came into existence, varying from a pitch of 45 degrees to one exceeding, at times, even 60 degrees. Timber roofing was often used to cover vaulting as it had in the Romanesque period, but it no longer rested on the back of the vaulting as it had previously. Where this style was used the roof stood entirely clear, without a tie beam but with a system of diagonal bracing instead. Throughout the Middle Ages it seemed that designers tried to avoid the unsightly tie beam, substituting forms less structurally sound in order to gain a greater impression of height in the interiors. Despite this attempt at avoidance we find the tie beam very much in evidence throughout all periods from the Norman to the Perpendicular. One particular point worth mentioning about this type is the fact that tie beams during this time were rarely horizontal but were usually cambered.

Brandon in "The Open Timber Roofs of the Middle Ages" (London, 1849) considered that roofs of the period could be divided into four types, drawing his examples from various

churches in England. The tie-beam type already noted was well illustrated at the North Walsam Church in Norfolk. Trussed rafters were another major type as exemplified at the Ely Cathedral. Structurally imperfect but giving beautiful results was the third style, the hammer-beam roof, often described as "an imperfect tie beam of which the middle part has been removed." The interiors of many medieval halls such as those at Westminster (1399) and Eltham still show the beauty inherent in this type, although many have since been strengthened with iron tie rods. A simplification of the hammer beam resulted in a fourth class, the collar-braced roof, as constructed at the St. Mary Magdalen Church, Pulham, Norfolk. Curved braces and brackets in roof construction continued to be used in England well into the seventeenth century.

Generally speaking, the Renaissance brought no striking innovation in carpentry in Italy, although the bold projection of eaves was a feature of the times. Italian roofs still remained low-pitched, but steep roofs continued to be popular further north, especially in France where dormer windows became characteristic. The high-pitched roof, cut off flat or nearly flat at the top, was popularized by the French architect François Mansart (1598-1666), but neither he nor his more famous nephew, Jules H. Mansart (1646-1708), can be regarded as the inventor of the "Mansard" roof, used by Lescot, at least, long before. ³ Joseph Moxon's "Mechanik Exercises, or the Doctrine of Handy Works," begun serially in monthly parts in 1678, gave many points on building construction consistent with modern practice. There were differences, of course, notable among

them being the use of heavier timbers then and the practice of always tapering the principal roof rafters from plate to ridge. Everything considered, however, the technique of working with timber was highly developed by that time, and there is now little to be found in a modern carpentry book which is less than a hundred years old. As it has through the ages, timber still finds its main structural use in roofs and in floors. In uncongested communities where danger from fire is not too great and where timber is in abundance the nearly all-wood house remains very much in evidence. The main development in modern times has not been in the structural field, though, but rather in the field of wood preservation.

WOOD PRESERVATION -- Though modern wood preservation may properly be said to date from the days of the wooden ships and railroads of the early nineteenth century, attempts at preservation were made long before. In his "Treatise on Building in Water" (Dublin, 1776), George Semple mentioned early attempts in Italy and Holland. He noted that the Venetians burned and scorched timber in a flaming fire by turning it on a spit until a hard black crusty coal was formed on the surface. The Dutch, he found, coated their timber with a mixture of pitch and tar and then threw on a powder consisting of crushed cockle and other shells mixed with sea-sand.

The first experiments in this field seem to have been conducted by the English, French, and Dutch in the eighteenth century, often with very unsatisfactory results. Bichloride of mercury, or corrosive sublimate, originated with Wilhelm Homberg

in France in 1705, but it did not achieve any degree of popularity until patented in England by John H. Kyan in 1832. The use of zinc chloride, which received the name of Burnettizing from the English patentee William Burnett (1779-1861), was first used extensively by British shipbuilders and by the engineers who built the first French railroad. Copper sulphate was tried as early as 1767 in France, but it was not used at great length until applied to the ties and telegraph poles of the early railroads. The names of two men stand out prominently above the rest in connection with this process: the first, Auguste Boucherie, French physician and chemist, and the second, the Englishman Margary, who patented the process in 1837. A fourth process, the use of heavy oils of tar for preservation purposes, was tried in England and America as early as 1756 but with indifferent success. In 1832 Karl Reichenback, a German manufacturer, prepared a powerful antiseptic from wood tar which he called "Kreosote." Four years later Franz Moll patented a cumbersome process which used light and heavy oils of coal tar successively, and he, too, used the term "Kreosote" to designate the heavier oil. Then in 1838 the Englishman, John Bethell, took out a patent covering eighteen different substances. Among them was the description of coal tar thinned down with oil distilled from the same substance. It was this patent which formed the basis for the popular modern process of creosoting. In the early days of the process creosoting was simply a hand brush operation but open tank immersion soon followed. In order to improve the preservative qualities the pressure and vacuum processes were later introduced.

The above named processes enjoyed the most popularity, but

they were by no means the only methods tried during the nineteenth century. Coating with a kind of varnish, carbonizing the outer surface with a lamp flame, and impregnating with two reacting chemicals such as hydrochloric acid and water glass were all given a serious trial. Despite the various schemes which were brought forward, however, no completely satisfactory preservative appeared. So even today the modern engineer still looks for the answer to the age-old problem of how best to preserve his structural timber. possibly to provide drainage. Sun-dried brick was also used on structures other than small buildings as testified by the town Brickwork 31-32, 33 and 34 feet high.

In Mesopotamia, which broadly included Assyria, Babylonia,

EGYPT AND MESOPOTAMIA -- Besides granite and limestone the Egyptians have always had at least two building materials available: viz., the mud washed down from Central Africa during the annual inundations and the trunks of date palms. Inasmuch as the date palm provided the laborer with half the necessities of life, he was reluctant to use it too generously and so turned to the use of dried mud. Initially the mud was used in a wattle and daub style, after the fashion of birds' nests, but with the passage of time sun-dried mud bricks, toughened by the addition of chopped straw, came into use. Workers' marks indicate that these bricks were dried in the sun after molding and before laying. Their sizes varied greatly, being at least 4 inches thick usually, with a width equal to half the length. Bricks used in arch construction--which was rare--were thin and flat, those found at Ramesseum measuring 14 by 7 by 2 1/3 inches. In general, brick size increased from the Fifth to Seventeenth Dynasties

and decreased after the Twenty-first. Although the first mastabas or royal tombs were made of sun-dried bricks, the use of this material was largely confined to humbler structures. No foundations were used for the ordinary buildings, but concave walls were sometimes erected to resist the inundations. Even in these early times the builders often used a bond similar to the modern "English bond." The thickness of bed-joints hardly ever exceeded $\frac{2}{5}$ inch, and layers of alfa-grass were often placed in joints to give additional bond, or possibly to provide drainage. Sun-dried brick was also used on structures other than small buildings as testified by the town walls at El-Kab, 30 and 37 feet thick.

In Mesopotamia, which broadly included Assyria, Babylonia, and Chaldea, brick construction was known almost as early as in Egypt. Here, however, the bricks were generally taken from the mold and laid while still moist. Not only were damp and sun-dried bricks used, but burnt bricks were popular as well. The latter were used in places liable to disintegration from dampness, such as lower portions of buildings and external facings. These bricks were made of clay reinforced with chopped reeds. This mixture, kneaded by foot in shallow basins, was molded into bricks about 15 inches square and 4 to 10 inches thick and then burnt in an oven or kiln. Also used by the Chaldeans was a bituminous damp-proof mortar, sometimes reinforced with fiber. In early Persia sun-dried bricks were used for general purposes, but burnt bricks were used for vaulting and for other construction requiring high strength. Apparently their bricks were burnt by firing a pile consisting of alternate layers of dry grass and clay.

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GREECE AND ROME -- In pre-Hellenic Greece a primitive sort of half-timber frame dwelling was made of sun-dried bricks bedded in mud, with wooden beams built into the walls. Brick was also used for large construction in that era, if we may regard the Palace at Tiryns (c 1400-1200 B.C.) as typical. Here walls of crude brick were built on a base of masonry rubble bedded on clay. Extensive use of brick was made by the Hellenic Greeks, according to Vitruvius, but none has survived in their great buildings. In many cases the brick walls were covered over with stucco, as was King Mausolus' structure at Halicarnassus (c 350 B.C.), or with stone, as were the cellae of the Temple of Jupiter and Hercules at Patras.

Here again we are indebted to Vitruvius for our knowledge of building construction in Rome at the dawn of the Christian era. He noted that brick should be made of white and chalky or of red clay, or even of a coarse-grained gravelly clay. There were apparently, three kinds of brick manufactured in his day, the Greek Lydian used by the Romans, measuring 1 by 1½ feet, and two other kinds used by the Greeks, which were probably square. Half-bricks were also used. One mode of construction called for the laying of a course of full bricks on one face and a course of half-bricks on the other, bonded by alternate courses of the two different kinds. It was also common practice to leave a cavity behind the facings of a wall and on the inside build a solid wall some 2 feet thick, made of red dimension stone, burnt brick, or lava in courses, bound to the fronts by iron clamps and lead. The faces of the thin bricks then used were of little or no account on the surface of a wall, for mortar and bricks were laid in

horizontal layers of about the same thickness. Most of the Roman brick which has survived has done so as an element in the "concrete" mentioned in a later section, but there has been nothing found in the straight brickwork line which would tend to contradict Vitruvius.

THE DARK AND MIDDLE AGES -- Probably the most striking feature of Byzantine architecture was its dome construction, typified by Hagia Sophia ("Holy Wisdom") or St. Sophia, as it is commonly called, at Constantinople. Constructed by Anthemius of Tralles under orders from the Emperor Justinian during the period 537 to 563, this church--for many centuries past, a mosque--has remained particularly noted as possessing one of the most wonderful interiors in the world. Its enormous flat dome was formed of brick ribs, each 2 feet 4½ inches at the spring. Typical of the flat bricks of the time, these bricks measured 13 by 6½ by 2 inches. The mass of the walling was also done in brickwork with very thick mortar joints, later covered over by a veneering of varied and beautifully colored marbles. This period also marked the first time in which brick came to be ornamentally treated. In many important structures bands of bricks set diamond-wise on plan were placed around arches, and great flat wall surfaces were panelled into shallow arcading.

Prior to the ninth century, mosques in Cario were generally constructed with marble colonnades which had been taken from earlier pagan and Christian temples. A departure from the practice was begun with the ninth century mosque of Ibn Tulun which was erected with burnt brick piers measuring 4 by 8 feet. The

building is particularly remembered for its pointed arches (with a span of 15 feet), for many have attributed the origin of the pointed arch to this structure despite the fact that similar work had been done at a mosque at Samarra a few years before. From the eleventh to the sixteenth century brick was used extensively for houses but not very much for mosques. Then, from the sixteenth or seventeenth century up to comparatively modern times, the old towns of the Delta adopted the ornamental use of brick for the embellishment of façades. Emphasis was placed on the brickwork patterns by always pointing up joints with a brilliant white.

Returning to Europe we note that the main places of brick-building during the Romanesque period were centered in northern and central Italy. Typical examples of the use of brick in church architecture of the time were the square "campanile" of the Roman churches S.S. Giovanni e Paolo and S. Francesca Romana. Italian brick sizes in the Middle Ages varied from $9\frac{1}{2}$ to $12\frac{1}{2}$ inches in length, from $2\frac{1}{2}$ to $3\frac{1}{4}$ inches in thickness, and were generally about 5 inches broad. Molded bricks and blocks of terra cotta were, however, every imaginable size. Throughout medieval times in parts of Italy, France, Spain, Germany, Holland, and Belgium brick was a popular building material for small structures, but it was exceedingly rare in England before the fifteenth century. The modern introduction of brick to Great Britain was probably due to the Flemish weavers who began settling in East Anglia from the fourteenth century onwards. A scarcity of stone in Flanders and in East Anglia stimulated their use of brick, so that by 1450 many brick buildings had appeared. English sizes were not too different from those of the Italians, a typical brick measuring $9\frac{1}{4}$ by $4\frac{1}{2}$

by $1\frac{1}{2}$ to $2\frac{1}{2}$ inches. One noticeable feature of late medieval English brick-work was the tendency to indicate and emphasize bond on the surface of a wall by means of darker colored bricks. One favorite pattern used headers of black contrasted with stretchers of red. Some fine examples of Tudor checker-work may still be seen at Hampton Court Palace, St. John's College, Cambridge, and Layer Marney Towers, Essex. In general, the brick-work of this period was more nearly allied to modern work than was that of the Romans, but bricks were still thinner and mortar still thicker than is the use today.

LATTER 17th CENTURY TO MODERN TIMES -- Interest in brickwork became particularly strong in England during the second half of the seventeenth century. The Fire of London led to a substitution of brick for many of the half-timber houses in the city, and the strong Dutch influence at the Court of William and Mary added encouragement to this type of construction. Then, too, the denudation of the English forests to provide for the expansion of the fleet advocated by Pepys and his colleagues provided yet another incentive. The period was also marked by the rise of the professional architect who was not the master craftsman that his predecessor had been but who was closer to the scientific designer of today. Each of these factors contributed in some part to the change which came about in brick construction during the latter part of the seventeenth century and early part of the eighteenth.

Face joints were reduced to the finest dimensions, and mortar appeared as an adhesive necessary to the bricks but forming no

proportionate mass in the wall. Thus the bonding of bricks with each other became increasingly important. The adhesion of the bricks to one another, for which the mortar was necessary, became a secondary constructive consideration, not to be depended upon for resistance to thrust or pressure, and the bond which the bricks could supply to each other became a scientific and technical problem. Two systems of interlacing the bricks so that pressure could be equalized came into general use and have remained to the present day--the English bond and the Flemish bond. The English bond, consisting of alternate courses of headers and stretchers, has found its main use in thicker walls, two or three or more bricks thick. Consisting of alternate headers and stretchers in each course, the Flemish bond has been popular for its looks and has been used largely in intermediate thicknesses of one and one-half to two and one-half bricks. In common brick walls it is now regular practice simply to insert a row of headers every sixth or seventh course. Following a relatively inactive period during the eighteenth century, brickwork came back strongly in the latter part of the nineteenth century, and has remained to this day one of the most popular types of construction in the small dwelling field.

Masonry

EGYPT -- Fundamentally the word masonry means "building," but in a more popular sense it has come to be thought of as describing the art of working in stone. And when one discusses working in stone, it is difficult to draw the line between simple

building construction and architecture. Although some structures found at Nippur and Tello in Chaldea seem to date from the fifth millennium B.C., the best examples in stone prior to Greece have come from Egypt. The Egyptians were well supplied with stone, using alabaster, basalt, diorite, granite, limestone, and sandstone. They used tubular drills and emery in saw blades to cut the hard stones and rocks, and used sand to cut the softer stones. Since they had no sizable lifting machinery much speculation has arisen as to how they managed to hoist the large blocks of stone used in their pyramids and temples. Herodotus mentioned the building of a huge inclined causeway of stone to the Great Pyramid on which the blocks may conceivably have been dragged. Flinders Petrie, the noted Egyptologist, has suggested that the stone blocks may have been raised by tilting them to one side, inserting a wedge, then tilting the other way, inserting a wedge from the opposite side, and so on in successive stages until the block had been elevated to the desired height. It is also possible that sand was dumped at the building site at a pace which kept the sand level the same as that of the construction work. Handling of the huge stones with this arrangement would continue to be the same jockeying sort which was probably carried out on level ground. When erection had been completed, it would be a simple matter to excavate the built-up layers of sand from the interior and exterior of the structure. That the Egyptians were capable of moving huge weights is evidenced by the fact that some of the obelisks are judged from their remains to have been over 500 tons. To the person versed in modern construction methods the handling of such weights by such crude means might

seem difficult to believe, but it must be remembered that slave-labor was plentiful and cheap, and time was not the important factor it is today.

Apparently a mortar of lime and sand was not used, although lime and plaster-of-Paris--the carbonate and sulphate of lime--was used. In "The Arts and Crafts of Ancient Egypt" (Edinburgh, 1909) Flinders Petrie noted, but could not explain, the mystery of plaster in the pyramid joints. Here were blocks weighing 16 tons which, presumably, could not slide freely, yet whose vertical joints 5 feet high and 7 feet long were filled with a plaster film only 1/50th of an inch thick. The thought has been advanced that the blocks were worked to such a smooth state that they were enabled to slide on the film of liquid mortar included between them. In much of their construction the Egyptians used metal and sycamore dowels to secure the blocks in position. Dovetail-shaped dowels were used to connect the separate parts of their large columns which were seldom monolithic. Many of their great temple walls were built in two thicknesses with a through vertical joint but with no bond stones, and the space between the battering walls of their pylons was often filled with sand.

Of all the creations of the ancient world none have evoked more awe, none have been the subject of more controversies, none have provoked such universal interest as have the Pyramids of Egypt. Remains still standing indicate that at least thirty-seven of these royal tombs were built at intervals along a line nearly 70 miles in length on the western, and more desert side of the Nile. Probably the oldest of these structures is the step pyramid at Sakarra, built under the Pharaoh Zoser of the Third

Dynasty by the "wise man" Imhotep, often considered the inventor of building in stone. Best known of these monuments are the three at Gizeh, about 7 miles from Cairo, which were built by the second, third, and fourth kings of the Fourth Dynasty, Khufu or Cheops (c 2900 B.C.), Khafra, and Menhaura. Greatest of these is that of Cheops, averaging about 760 feet on a side with a height above the mean level of the base of approximately 455 feet (original height, probably 484 feet). It is obvious that this and the other pyramids similar to it were built first in a step section, and then had the sloping surface of masonry applied. The labor put into the pyramid of Cheops alone has been estimated at anywhere from 100,000 to 360,000 men working for a period varying from twenty to thirty years.

Another bit of funereal architecture in the Ancient Kingdom was the mastaba, the shrine of a lesser man just as a pyramid was the shrine of a king. The mastabas were rectangular buildings built with an exterior batter which came about through stepping back slightly each succeeding course of masonry. In the Middle Empire, from the Eleventh to the Seventeenth Dynasty, the emphasis seems to have shifted to rock-cut tombs or caves. One of the most outstanding examples of this type of construction has been uncovered at Beni-Hassan on the Nile, some 250 miles from the Mediterranean.

With the passing of the Shepherd Kings the great Theban kingdom arose about 1700 B.C., and with it came a renaissance in building construction. The period is remembered particularly for its magnificent masonry temples or royal shrines which come to the mind of most when Egyptian architecture is mentioned.

Greatest of these temples was the one at Karnak (c 1700-980 B.C.) which was developed slowly according to the same general architectural plan for a period exceeding seven centuries. The ceiling of the central portion of the Hypostyle Hall of this temple is over 75 feet above the floor and the central columns measure 10 feet 7 inches in diameter. In its completed form the building measured about 1200 by 350 feet. Its style was entirely consistent with the rest of Egyptian architecture as we have come to know it, being ponderous and massive with heavy stone lintels resting on huge stone columns.

From information gained to date, however, there is little to be said of Assyria and Persia. Stone in Assyria seems to have been used largely for sculpture and lower facings, while the principal building materials were brick and tile. As a consequence, the Assyrian structures have not stood the test of time as have the Egyptian, but have, for the most part, crumbled into masses of shapeless rubble. It is evident from findings thus far that the long stone lintels of the Egyptians were little used, and that openings were spanned by arches and vaults formed of small pieces of brick and tile. Where the architecture of Egypt appears to have been one of temples, symbolism, and mystery, that of Assyria seems to have been more one of palaces, fortifications, and fighting. Most important and complete of the ruins which have been unearthed in Assyria has been Sargon's Palace at Khorsabad (c 720 B.C.). Its remains show clearly the Assyrian tendency to place a decorative veneering over a base of perishable material.

The Persians, whose ascendancy began about the middle of the sixth century B.C., built the decorative portions of their

buildings in solid stone with brick connecting the walls between. Thus at the palaces at Persepolis, built during the time of Darius (521-486 B.C.), and Xerxes (486-465 B.C.), the gateways and columns stand free, the soft bricks which once connected them having been washed away by the rains of centuries. Evidences of both Assyrian and Egyptian influence can be deduced from the Persian style and use of materials. In the Hypostyle Hall of Xerxes the thirty-six columns were arranged in a manner similar to earlier Egyptian examples, but the columns themselves were much more slender, indicating that a wooden roof might have been used. From information gained to date, however, there is little to encourage the belief that the architecture of Assyria and Persia had any profound effect on that of the civilizations which followed.

PRE-HISTORIC GREECE AND BRITAIN -- In Greece, on the shores of the Eastern Mediterranean, and in the Mediterranean islands many structures in stone have been found which have been vaguely termed "Pelagic," though just who the Pelasgi were and when they lived is subject to speculation. Remains at Knossos and Tiryns indicate that these people were well able to plan and execute large structures in stone, and the period during which this construction took place might be almost anywhere between 2000 and 1000 B.C. It was an architecture mainly of fortress-like dwellings and tombs characterized by an arrangement of large polygonal stone blocks, sometimes roughly squared, popularly called "Cyclopean" masonry. The size of stone involved in this type of construction is typified by the lintel at the Mycenaean Lion Gate, 16½ feet long,

8 feet wide, and over 3 feet thick at the middle. Triangular doorways, formed by beams of stone leaning against each other, were not uncommon but the post and lintel was used as well. The Pelasgic builders also made extensive use of the corbeled vault and arch. At Mycenae the covered vault known as the Treasury of Atreus is an excellent example of the corbeled dome of this period, having been built with oversailing courses of stone in level beds to a height of nearly 50 feet. In the middle Minoan period (c 2200-1700 B.C.) particularly fine masonry work was done, resulting in finely squared and closely fitting blocks with faces as large as 5 by 6½ feet. Wall tiles were secured to the masonry by dovetailed-shaped bronze clamps.

Though separated from the Pelasgic construction by a continent, the greatest of English megalithic monuments at Stonehenge probably dates from about the same time and certainly exhibits features in common with those of the Mediterranean work. Still standing at Stonehenge are cumbrous blocks of stone indicating an original lay-out of two circles and two rows in the form of a horseshoe, all concentric. The outermost circle of 'trilithons' originally consisted of thirty upright hewn stones, sixteen of which still stand, joined together by stone lintels, five of which remain. These lintels have been dovetailed together and mortised to the uprights with a great deal of skill, indicating that the builders had considerable experience with stone construction. Another prehistoric type of construction carried out in Britain deserving of mention here is the Gallic wall and vitrified fort, probably antedating the Roman occupation. The

Gallic walls found in Scotland consisted of two parallel masonry faces tied by timber beams, with the space in between filled with rubble and timber. Apparently the vitrified forts were simply Gallic walls which had been burned, the high Scottish winds raising the temperature to such a point that the stones were fused.

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HELLENIC GREECE -- Manpower in Hellenic Greece was probably not wasted to the extent it was in Egypt and Mesopotamia, for the Greek notion of beauty was not identified with mere bigness. The Greeks worked largely with limestone, as at Aegina, Corinth, Olympia, and Paestum, or with marble, as at Athens. They still employed the post and lintel as a basic construction feature, but they developed a type of architecture which has remained famed through the ages for its relative lightness and grace. In some cases the lintels were hollowed on the inside, making them something like the modern iron box girder. This reduction in weight diminished the risk of failure to the extent that openings of 13 feet were spanned with lintels only 13 inches in depth; however, the carrying power of such lintels was nearly all absorbed in supporting their own weight. The columns of their temples-- most of the Greek construction that we know of being temple architecture--were characterized by three styles (which included the Entablature in addition to the column) viz., the Doric, Ionic, and Corinthian, and were predominantly on the outside of the buildings, whereas Egyptian columns had been inside. In the sixth century B.C. wooden dowels were used for the drums of columns, and from the fifth century on iron

fastenings were systematically used in many places. Walls were of various kinds. One type was composed of all through-stones showing on both faces, another had the through-stones in every alternate course, while a third had ashlar facing throughout, a bit of rubble core, and through-stones at intervals. We have no evidence that they used mortar in their ashlar work.

Probably the oldest Greek temple of which traces are left is the Heraion at Olympia, dating perhaps to the eleventh or twelfth century B.C. The wide spacing of its stone columns indicates that it had a timber roof, usual in Greek construction. Progress in masonry construction advanced in Greece with the centuries until under Pericles Athens developed those artistic qualities which made her the wonder of the world. Such buildings as the Parthenon (c 440 B.C.)--ascribed to the architect Ictinus, who later built the temple of Apollo at Bassae--and the Propylaea (c 430 B.C.) built by Mnesicles, testify to the design and construction abilities of these engineers of a by-gone age. Not all Greek temples were, like these, of finely finished Pentelic marble, but many, like the later temple of Zeus at Olympia, were of a stone coarse in texture which was covered with stucco for the finish of details. Mention here should also be made of the great temple of Diana at Ephesus (c 356 B.C.), noted for its grand scale and boldness of design and execution. The distance between the abaci of the two columns at the center was 23 feet, an immense space to be bridged by a single block of marble. Numerous other structures are worthy of attention as well, but it is sufficient for our purpose to note that they were generally well-constructed from both the structural and aesthetic

viewpoint and had considerable influence on the Roman world these great construction jobs may be said from noting the quality which followed.

GREAT WALL OF CHINA -- From the evidence available there is little to support the view that there was any interchange of ideas on construction methods between China and the West during the time of Classical Greece and Rome. Despite the lack of continuity to our story, some mention should be made of the Great Wall of China, the bulk of which was built during this time.

Most of the work on the Wall is usually assigned to the period c 228-210 B.C., and the name generally associated with it is that of the Emperor Ch'in Shih Huang Ti. The Wall probably existed in part before his time but he, at least, completed and strengthened it. Designed to keep out the barbarian hordes of that long past era, the Wall still stands, some 1400 miles in length. Consisting of facings of brick or granite filled in with earth, it averages over 20 feet in height. On top it forms a road 13 feet wide, and at regular intervals of approximately 100 yards it is fortified with a tower.

ROME -- Rome's splendor was made of many parts, not the least of which were her great structures in stone: her temples, triumphal arches, theatres, aqueducts, baths, basilicas, bridges, and palaces. Where the architectural expression of the civilizations which had preceded her had been confined to one or two types, such as temples or fortress-like palaces, the Roman expression spread itself over every aspect of private and public life. Some idea of the type of men who conceived and executed

annoyance, the Roman architect concentrated on the facings and these great construction jobs may be had from noting the qualifications desirable for an architect according to Vitruvius, in the introduction to his first chapter on architecture: - "Let him be educated, skillful with the pencil, instructed in geometry, know much history, have followed the philosophers with attention, understand music, have some knowledge of medicine, know the opinions of the jurists, and be acquainted with astronomy and theory of the heavens."

Both the post and lintel of the Egyptians and the arch and dome of the Etruscans were used by the prolific Roman builders. Their chief building stones were a soft tufa, a hard limestone called travertine, and a hard volcanic rock known as peperino. Vitruvius recommended that stone used for construction be quarried in the summer and allowed to weather for two years. If in good shape at the end of this period the stone should be used above ground, but if deteriorated, it should be thrown in the foundations. He had a high opinion of Greek construction which he described in some detail and which applied to parts of Roman work as well. For instance, in building walls the Greeks laid courses of hard stone or lava, binding the upright joints by interchanging the direction of the stone in the courses. Construction in which all courses were equal was termed "Isodomum," and that in which the courses were unequal was called "Pseud-isodomum." Another type of walling was that in which the facings were finished and other stones were left in their natural state, the tying being accomplished by alternate bonding stones. The Greeks made this type of wall solid but, noted Vitruvius with

annoyance, the Roman workmen concentrated on the facings and just threw stones and mortar at random in between. Perhaps this Roman failing is better understood when we realize that although the facing was the work of skilled craftsmen, the carcass was usually built by unskilled slaves, free men under *corvée*, or soldiers with no fighting to do. Of course this criticism cannot be levelled at all Roman work either, if we take the earliest known secular building of the Republican period--the Tabularium (c 78 B.C.) on Capitoline Hill--as an example. Here peperino blocks measuring 4 by 2 by 2 feet were laid alternately as headers and stretchers, with a thin layer of mortar in all joints, and tufa behind. In a later period dovetailed dowels were used for connecting ashlar blocks in successive courses; the joints were formed by running molten lead into the prepared dovetail hole after the block was laid.

Circular buildings and rectangular buildings, even polygonal buildings, were numerous in Roman work. To the three original Greek Orders they added two more, the Tuscan and a Composite of Ionic and Corinthian. Where the Greeks had used their orders as real structural features, the Romans, in many buildings such as the Colosseum (A.D. 80) and Theatre of Marcellus (13 B.C.), simply planted half-columns around the outside for effect while the arched construction did the work of support. It would seem from inspection of a large number of their arches that they preferred "flying" scaffolds resting on projecting stones to tall timberwork from the ground. Among their many feats with stone which have become particularly well-known is that of placing three tremendous blocks of stone--each over 60 feet long, 12 feet

wide, and 11 feet thick--end to end in a masonry of smaller stones, in the podium at the upper end of the Temple of the Sun at Baalbec (c A.D. 200). Much of their masonry work was done without mortar, as at the Pont du Gard, but it is in connection with mortar and concrete that their building construction reached its fullest expression, a point which will be discussed later in the section dealing with cement and concrete.

BYZANTINE AND ROMANESQUE PERIODS -- More than a century was to elapse from the time of the split of the Roman Empire and Church into Eastern and Western parts (A.D. 364) before the new style of architecture known as Byzantine began to clearly emerge in the East. Pre-Byzantine in an architectural sense, but probably the most noted stonework of the early Byzantine period, was the enormous monolithic lid or flat dome of Istrian stone, 33 feet in diameter, covering the Tomb of Theodoric at Ravenna (490). Handles for lifting this dome into place were cut out of the solid stone of the lid and have remained to this day jutting from the mass of the structure. For the most part, the Byzantine masonry was a development of Roman "concrete" construction, of which more will be said later.

Broadly speaking, that architectural period in the West between the fall of Rome and the rise of Gothic architecture might be called "Romanesque," though a further division of the period into "Early Christian" or "Latin" and "Romanesque" is probably more helpful. If we assign those structures roofed in timber to the Latin period and those vaulted in stone to the Romanesque, the structural differences will account for the differences in

style.

One important point to note is the fact that most of the construction during this period was ecclesiastical, in the form of a long building divided longitudinally into aisles by colonnades or arcades. We also find that the columns--having, in the main, been outside during the Greek and Roman eras--moved inside the building again. Where timber roofs were used the columns were slender and relatively far apart, but as heavier roofs developed, so too did the columns to such an extent that they became a compound type of support known as the pier. The semi-circular arch, after the fashion of the Romans, formed a distinctive feature of the Romanesque style, typified by the Cathedral and famed leaning Tower of Pisa (1006-1103) and La Trinité (Abbaye aux Dames), Caen (founded 1063). Despite the many fine structures which were erected during this period, it was generally true that a decline from previous standards had set in. Roughness and lack of finish were characteristic, and construction was clumsily heavy according to the Gothic standards which followed.

THE GOTHIC PERIOD -- The Gothic period of architecture which arose in the latter half of the twelfth century stands out in advance of even Greek building as a style in which masonry assumed its maximum importance. Ecclesiastical architecture was absolutely dominant in this period, emphasizing verticality and lightness. Stone blocks comparatively small in size were used, for roads were poor, wheeled transport was negligible, and the main carriage of materials had to be accomplished by pack animal. The

elaborate Gothic molding and profuse amount of carving on these structures can be attributed to the abundance of labor and high level of craftsmanship ensured by the trade guilds; this, and the patient piety of the many who must have toiled on these great churches over the centuries. Just who the master-builders were who designed and supervised the construction of these monuments in stone is, for the most part, unknown. Erwin von Steinback (c 1244-1318), who played a large part in the construction of the Strasbourg Minster, is one of the few great architects and engineers of the medieval period whose name has been preserved for posterity. For the most part, if any name at all was attached to one of these magnificent works, it was that of some presiding bishop or other prelate. Times have not changed much in that respect, however; when most large modern projects are completed the placques and dedication platforms are monopolized by the politicians and promoters, and the engineer, his work completed, is relegated to the background.

In the later Romanesque period the French, and to some extent the English, had succeeded in covering their churches with solid cross-vaulting, but with difficulty. Adherence to the traditional Roman semi-circular arch resulted in many different unsatisfactory compromises which were finally resolved by the introduction of the pointed or broken arch. With the introduction of the broken arch the shape and curve of the vaulting-space was determined by the ribs, where before the intersecting of the surfaces had determined the line of the groins, with or without ribs. Instead of a series of separate compartments the vaulting now became one contiguous design. Oblong bays with all piers similar became normal. The whole form and development of

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Gothic architecture was governed, therefore, by the vaulting; it caused the adoption of the pointed arch, the enlargement of the buttresses, and the introduction of the flying buttresses. It also had considerable influence on the subsequent development of the ground plan of the piers.

The Gothic style reached its heights in France and England and was developed to a lesser extent in Italy, Germany, and Spain. All over Europe beautiful medieval churches in this style still stand, relatively unchanged from the time they were completed. The completion date for most is a nebulous thing, however, for many were in the process of building for centuries and some have never been entirely completed. It is difficult to pick out the structure which exhibits all the best in Gothic, but few will deny the richness of expression embodied in the thirteenth century cathedrals at Chartres, Reims, and Amiens. Within itself and in each country the Gothic style underwent a slow change, starting with the Transition from Romanesque in the twelfth century and ending with the Flamboyant Decorated style in France and the Perpendicular style in England in the sixteenth century. At this time the wave of the Renaissance in building construction began to make itself felt in the northern countries.

FROM THE RENAISSANCE TO MODERN TIMES -- From the downfall of the Roman Empire to the Renaissance, which began in Italy in the latter part of the fourteenth century, practically the whole of architecture was devoted to the Church. With the revival came the old Roman spirit of building many different types of structures

in a grand manner; thus, this period came to be characterized not only by churches, but by palaces, theatres, and public buildings as well. It was not the period in stone that Gothic had been, however. Many imposing buildings such as the Pitti and Strozzi palaces at Florence and the Chancery at Rome were constructed with walls of brick or rubble faced over with a comparatively thin stone layer. It was a period in which good craftsmanship prevailed and in which external finish was skillfully applied, but it lacked the variety and interest of the Gothic. Much of the work of the period was dull, being clothed in the classical "Orders."

In the humbler realm of the simple house, stone blocks continued to be favored in those areas where stone could be obtained without too much difficulty. In England, for instance, the spirit was essentially Gothic even after Wren had commenced St. Paul's in the latter half of the seventeenth century. Until the beginning of the eighteenth century Yorkshire cottages were, for the most part, built with masonry walls 2 feet thick in a style well-suited to the wild moorland. During this same period dwellings in the Cotswolds were developed along more graceful and refined lines. Walls 18 inches in thickness were usual in these houses, but thicknesses of 2 feet and even more were not uncommon. They were built of rubble stone in thin courses or ashlar in thicker courses, often in the dry and with the stone undressed.

The nineteenth century was an age of revivals in which little was contributed to architecture or to the art of building in stone. It was a period which saw the beginnings of iron and steel, cement and concrete. The tremendous strides taken in

to 3 inches externally. The development of concrete during the twentieth century give indications that the old methods of building in natural stone will all but disappear as the new "artificial stone" moves into the foreground.

Plaster, Cement, and Concrete

PLASTER -- Plaster, though never used in a structural sense, has had one of the longest histories of all the materials used in building construction. A plaster of burnt gypsum--like the modern "plaster of Paris"--up to 2 or 3 inches thick was used by the ancient Egyptians to fill up holes and cracks in stone walls. It was also used on brick as a hard facing--1/10 to 1/16 inch thick--which provided a surface for Egyptian paintings. In some instances it was mixed with hair and placed as a sheet of about 1/2-inch thickness on wooden partitions laid on a canvas base, or on reeds laced together with cords to form a primitive lathing. Little, if any, plaster was used by the Assyrians, but discoveries in Mycenae and Knossos have indicated that the pre-historic Greeks and Cretans knew of it. To create the effect of marble the Hellenic Greeks used a stucco made with marble dust, which they applied to some of their limestone temples. Remains of this type of masking have been found in Aegina, Corinth, Paestum, and Sicily, and a similar material, 1/12 to 1/3 inch thick, has been found in Etruscan tombs in Italy.

The importance of stucco in Rome may be judged from the fact that Vitruvius allotted more space to this than to any other material. Thicknesses used varied from 1/16 inch internally

to 3 inches externally. Its excellence was such that its polished surface has been compared with a mirror. Roman fresco painting and modelling in stucco were equally famous and inspired much of the noted plasterwork done by the Adam brothers in England at the end of the eighteenth century. To a great extent the art of plastering was then lost during the Dark Ages, but some of it has been found on Anglo-Saxon churches in England and in Merovingian and Carovingian churches in France masking irregular rubble masonry. During the Gothic period plaster was used almost wholly inside of churches on rubble walls and vaults to furnish a smooth surface for fresco painting.

After the Fire of 1212 a London ordinance was drawn up stipulating that all houses then covered with reed and rush should be plastered. This resulted in the well-known "wattle and daub" construction in England and elsewhere which remained in general use until Renaissance times. In this method slats of cleft oak were nailed to horizontal timbers of framing, and between these were interwoven the "wattles," hazel sticks $\frac{1}{2}$ to 1 inch in diameter. To this framework was added a thick layer of clay mixed with straw. Even today cottages made of mud and cowdung can be found in various localities such as Oxfordshire or the West country. During the Renaissance the attention of the builders was focused on the "stucco duro" of the Romans, with the result that the lost art was resuscitated about 1488. At that time Donatello mixed pounded brick and glue in his stucco and produced a mixture closely resembling terra cotta. Forty years later his method had spread through Europe as far north as England. The old wattle and daub gave way to lath and plaster, and by the

sixteenth century lath and plaster ceilings were common in large houses. At the end of the eighteenth century England experienced another revival of "stucco duro" by the brothers Adam. The invention of Portland Cement early in the nineteenth century then ushered in the modern era of plasterwork which is used now in or on almost any structure of consequence.

ROMAN CEMENT AND CONCRETE -- The generally accepted notion about the origin of concrete is that the Romans were first to use it, although some claims have been advanced for its earlier use.

In "Concrete and Reinforced Concrete" (London, 1920) W.N. Twelvetrees shows a fresco of the Temple of Ammon at Thebes which, he claims, depicts the making and use of concrete by the early
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Egyptians. He also states, without citing any examples, that prehistoric concrete buildings have been discovered in Mexico and Peru. It appears that the art of burning stone to lime and making a mortar of it was not used by the Romans before the third century B.C. The Emporium on the bank of the Tiber, dating from
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about two centuries before the Christian era, is the first known to have been constructed with lime mortar, but it was soon followed by many other structures made of a "concrete" consisting of a rather indiscriminate mixture of rubble and mortar.

By the beginning of the Christian era the use of the various materials in the making of Roman concrete was somewhat standardized, judging from the writings of Vitruvius. He urged testing sand by throwing it against a white garment and shaking. If the garment was not soiled and no dirt adhered to it, the sand was suitable. He did not favor the use of sea sand because it dried

slowly necessitating pauses in the work, discolored stucco, and made weak walls which could not carry vaultings. For concrete structures he recommended pit sand--for stucco, polished river sand. He went on to say that lime must be burned from a white stone, and that the proper mixture of lime and sand varies with the type of sand. Recommended proportions were three parts of pit sand to one of lime, or two parts of river or sea sand to one part of lime plus a quantity of burnt brick pounded and sifted. Vitruvius also paid tribute to the cement which played such a large part in making Roman construction famous. Found in the neighborhood of Baiæ and in the country around Mt. Vesuvius, pozzolana--as it was called--contributed greatly to the strength of structures when mixed with lime and rubble. It was also extremely valuable for use in sub-aqueous work, for piers set under water with it were rapidly hardened into place.

Though much has been claimed for Roman concrete--and perhaps with a great deal of justification--it should be realized that it bore little resemblance to the more scientifically mixed concrete of today. As applied to walling, Roman concrete consisted of small stones and of lime mortar in alternate layers filled in between two outer facings of stone or brick without falsework or centering. A typical mass between the two facings might consist of layers of mortar 4 to 6 inches thick, composed of lime and pozzolana or of lime and coarse sand, alternating with layers of pebbles of compact tufa or black lava capable of passing a 3-inch ring. Unfaced concrete was generally relegated to foundations but faced concrete came in a variety of forms. One type

of facing was the "opus incertum," which consisted of irregular pieces of stone arranged in no particular system. Another type was the orderly diamond-shaped "opus rectilatum," consisting of stone spikes with faces about 3 inches square arranged diagonally. Triangular bricks which secured a good bond with the core of the wall were also popular, as were facings of marble slabs and regular masonry.

The excellent quality of their cement made many of the Roman structures appear almost monolithic. A case in point is the dome of the Pantheon (A.D. 123), which is one of the best examples of the tenacity of ancient cement. The dome has a diameter of 142 feet with an opening in the top 30 feet in diameter. It was built with thin layers of brick, but the mortar appears to be the main material, forming, as it were, a huge concrete shell.

With the passing of the Romans the art of making good mortar began to deteriorate and was not successfully revived until the nineteenth century. In the Byzantine world walls were built more or less along Roman lines, the emphasis being more on brick than on stone. During the Gothic period a mixture of mortar and stone was sometimes used for foundations and also for bits of above-ground construction, but this mixture could hardly be termed concrete. As late as 1770 George Dance, in making the principal foundations for the Newgate Prison, threw in whole and broken brick and cartloads of mortar in the ratio of one to four, but even this was not concrete.

EARLY MODERN LIME RESEARCH -- The beginnings of modern concrete French engineer, Louis I. Vicat, and the German chemist, Johann

may be traced back to the middle of the eighteenth century when John Smeaton (1756) began experiments in connection with the proposed Eddystone Lighthouse. He determined that the property of setting under water could be achieved by lime which had been mixed with a proper amount of clay. By his experiments he offset the prejudices of almost two thousand years--from Vitruvius in Rome to Belidor in France and Semple in Britain--that hardness and whiteness of the stone gave lime its qualities. Smeaton's experiments were followed by those of Bryan Higgins, an English physician, who set out in 1774 to find an equal to the famed Roman cement. In 1779 he was granted a patent for a mortar of clean graded sand, lime, and bone-ash which could be used not only for stucco but also for "forming artificial stone, by making alternate layers of the cement and of flint, hard stone, or brick (just like Roman construction), in molds of the figure of the intended stone." In the following year he produced "Experiments and Observations---Improving---Calcareous Cements" in which he offered proofs that materials then often put in mortar such as serum of ox-blood, skimmed milk, or various oils and sulphur should not be used.

In the generation following Smeaton many investigators began work on the problem, not only in England but in France, Germany, and Sweden as well. In 1810 Edgar Dobbs took out an English patent for an artificial "Roman" cement which he prepared from limestone and clay (50%). He formed the mixture into briquets and burned them just about enough to expel the carbon dioxide. This work was soon followed by that of two notable men--the French engineer, Louis J. Vicat, and the German chemist, Johann

F. John. Both had been engaged on research in this field for several years--Vicat since 1813, for instance--before they developed in 1818 a hydraulic lime which bore out Smeaton's findings. Another contributor of note was General Treussart who seized upon an idea given him by John Rennie to further the use of lime in underwater work. Treussart immediately saw the possibilities when Rennie described the difficulties encountered by the workers in trying to move from the river bed at the site of the Waterloo Bridge a solidified mass of gravel and accidentally dumped lime. Then in 1822 James Frost, an Englishman, produced an artificial hydraulic cement similar to that of Vicat.

NATURAL CEMENT -- While the attention of most investigators was concentrated on the improvement of lime, a new material slowly and unobtrusively entered the field--natural cement. Its modern discovery was made by J. Parker of Northfleet, Kent, in 1796. He noted that nodules containing both clay and limestone found at and near Sheerness on the Isle of Sheppy near the mouth of the Thames had the property of hardening rapidly with the addition of water, after having been burned and ground to a fine powder. The raw material for this substance, which he patented and called "Roman" cement, was later found at Harwich and elsewhere. Its adoption by the engineering profession in England was slow, however, until after its first large-scale success in Brunel's Thames Tunnel, begun in 1828 and completed in 1843.

The discovery of natural cement in the United States went hand in hand with the excavations for the early canals, when cement rock was laid bare for the first time. Generally, the

rock was found along the lines of the canals under construction, and thus became well-known among construction men at a relatively rapid rate. Canvass White, engineer on the line of the Erie Canal, is credited with being the first to realize the value of the cement rock which was uncovered near Syracuse in 1818. He took out a patent shortly thereafter, giving the product the name of "water lime." As was the case in England this new material was used hesitatingly at first, only for face work or for pointing masonry which had been laid up in lime mortar. The beginnings of the natural cement industry were made in 1825 in Ulster County, New York. The center of the industry was located in the town of Rosendale, a name which later came to be applied, more or less, to all American natural cements. Production rose with the years, reaching a maximum of ten million barrels a year in 1889. Since that time it has rapidly and steadily declined as Portland cement has moved to the fore. Though the industry is almost extinct now, natural cement is used sometimes in massive masonry where weight rather than strength is the essential feature. It is also used in specialized circumstances where a quick-setting cement is desirable. Though natural cement sets more quickly than Portland cement, it develops strength more slowly and is subject to much wider variations in characteristics, making it less desirable as a construction material.

PORTLAND CEMENT -- The American Society for Testing Materials
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 defined (1933) Portland cement as follows:- "Portland cement is the product obtained by finely pulverizing clinker produced by

the early years. The first American manufacturing experiments

calcining to incipient fusion an intimate and properly proportioned mixture of argillaceous and calcareous materials, with no additions subsequent to calcination excepting water and calcined or uncalcined gypsum." Joseph Aspdin, a bricklayer of Leeds, is popularly known as the inventor of Portland cement, although the present cement known by that name probably differs a great deal from the one he invented. In 1824 and 1825 he secured patents for "Portland cement," and it is known that he began making this cement in 1825 at Wakefield, a few miles south of Leeds. He named the product "Portland" it seems, because it resembled in color and texture the oolitic limestone found on the Isle of Portland off the south coast of England. It appears that at first the material was largely used for stucco, but in time its value in mortar and concrete came to be appreciated. Inasmuch as Aspdin kept the details of his process secret and worded his patent vaguely, we cannot be at all certain that his process--which may not have been carried to a high enough temperature--or product bore much resemblance to present-day Portland cement.

By 1845 many English firms were engaged in making Portland cement in one form or another, but its introduction into the United States was very slow. Natural cements had been in use in America for half a century before the first Portland cement was imported from England in 1866. At a later date it was also imported in quantity from Belgium and Germany. Little information was available as to its proper use, but it seems to have been used largely in the construction of concrete walks during the early years. The first American manufacturing experiments

were begun in the seventies under the direction of David O. Saylor at Coplay, near Huston, Pennsylvania. By 1875 Saylor found that he could produce a good native Portland cement by mixing cement rock with nearly pure limestone before burning. As a result, his product set a standard for American Portland cements which was unchallenged for years. At just about the same time that Saylor's experiments proved successful, Portland cement gained the recognition due it in connection with its use on Hads' bridge at St. Louis and on the Drexel Building in Philadelphia. of 1889 followed by his success in 1890 in developing a good hydraulic cement on a large scale. He also contributed

CONCRETE -- We have previously noted that Roman "concrete" and the various rubble and mortar mixtures of the Middle Ages bore little resemblance to the scientific mixtures of cement, sand, stone, and water called concrete today. Strictly speaking, concrete as we know it is a very modern material; even the name does not seem to have been used before the early part of the nineteenth century. A forerunner of modern concrete was a type of lime-concrete described by the Irish engineer, George Semple, in his "Treatise on Building in Water" (Dublin, 1776). In 1833 Poirel, a French engineer, in rebuilding the breakwater at Algiers used for the first time concrete blocks of lime, sand, and pozzolana instead of the "pierres perdues" which had been used at Cherbourg and Plymouth. These blocks, which were cast in place, each measured between 150 and 200 cubic meters. The "first and most remarkable example" of concrete used for other than foundations was, according to Charles W. Pasley (1838), the sea wall at East Cliff, Brighton, planned

by Thomas Cooper. The wall was 2 feet 6 inches thick at the top, was 60 feet high in places, and had a maximum width at the base of 22 feet 6 inches.

Pasley's work, "Observations on Limes, Calcareous Cements, (etc.)," in which the Brighton sea-wall was described, was the first comprehensive study of the subject written in English. An officer of the Royal Engineers, Pasley began his experiments at the engineer school at Chatham in 1826 and first published his treatise in 1838. In the book he described his unsuccessful attempts of 1829 followed by his success in 1830 in developing a good hydraulic cement on a large scale. He also contributed much to the early testing of cement mortar and concrete. In his opinion concrete should be used more as an assistant to stone and brickwork rather than as a primary material standing alone. Although he believed in using natural cement as a part of the concrete in underwater construction or in the lower parts of wharf walls or piers, he felt that the use of lime in place of cement was better for ordinary construction.

During the first half of the nineteenth century the use of rough concrete was confined almost wholly to foundations and walls, but as knowledge of and experience with the material increased in the latter half of the century, it was put to a number of different uses. In 1853 Francois Coignet--often called the "Father of modern concrete construction"--constructed a concrete roof with a span of 20 feet and a thickness of 12 inches. City pavements of concrete were first laid in Inverness, Scotland, in 1865, and later in the same decade (1869-70) concrete was used extensively on the Vanne Aqueduct of the Paris water supply, on

the Paris sewers, and on other public hydraulic works. The new material soon became the subject of many papers, especially in France and in the United States. One of the most important of these was Coignet's "Des bétons agglomérés appliqués à l'art de construire" (Paris, 1861). He admitted that the art of making and using concrete was only in its infancy, but he was confident that it could achieve success with intimate mixing, elimination of excess water, and careful tamping. Among other predictions concerning the use of concrete he foretold concrete pavements when the hardening time of three to four weeks then needed was reduced. His work served to inspire the first important American treatise on the subject, General Q.A. Gillmore's "Report on Béton Aggloméré, or Coignet-Béton" (Washington, 1871). By this time a new factor had begun to establish its importance-- iron reinforcement.

REINFORCED CONCRETE -- Although reinforced concrete did not achieve much recognition until the latter part of the nineteenth century, it had been talked about almost from the inception of Portland cement. As early as 1830 J.C. Loudon's "Encyclopaedia of Cottage, Farm, and Village Architecture" suggested flat roofs of cement with imbedded iron tie rods. About 1849 J.C. Lambot, a French contractor, actually constructed a rowboat of "wire mesh-work reinforcement embedded in concrete" which was shown at the Paris Exhibition of 1855. In the same year William B. Wilkinson, "plasterer and manufacturer of artificial stones," secured at Newcastle-on-Tyne

a patent for "improvements in the construction of fireproof dwellings, warehouses and other buildings, or parts of the same." For this purpose he recommended a reinforcement of hoop-iron tension rods. Fireproof floors for warehouse construction were also discussed in William Fairbairn's "On the Application of Cast and Wrought Iron for Building Purposes" (London, 1864), in which he illustrated concrete arches reinforced with imbedded tie bars.

Despite these early efforts, however, the origin of modern reinforced concrete is generally credited to Joseph Monier, the owner of a large garden establishment in Paris, who began making concrete

garden boxes in 1861. In order to secure lightness without sacrificing strength he made basins and reservoirs of cement in which iron netting was imbedded--an idea which he patented in 1867. Ten years later he extended the idea to a railway sleeper patent, then to floors, arches, footbridges, buildings, and the like. Basically his system called for the use of round reinforcing bars crossed at right angles to give a trellis effect.

Though he knew little of the theory of the matter, he was certainly a pioneer in construction; he was the first to combine iron and concrete scientifically so that they acted as a single unit of material. Another Parisian, M. Hennebique, labored from 1855 to 1895 in an endeavor to bring scientific theory and construction results in harmony with each other, and it is to him that much of the credit must go for the establishment of modern reinforced concrete. No discussion of early theory is complete without mentioning the name of the American Thaddeus Hyatt, who was perhaps the first to analyze correctly stresses in a reinforced concrete beam. The results of his experiments

of 1876 were published in the following year in London under the title: "An Account of some Experiments with Portland Cement Concrete, Combined with Iron, as a Building Material." Following Monier's success the idea spread rapidly to other countries. Whether it came directly from France or developed more or less spontaneously because conditions were right is open to question. Certainly the French were early leaders in the theoretical field. The American pioneer in reinforced concrete, William E. Ward, claimed that he had been led to experiment after watching some English laborers try to remove hardened cement from their iron tools. In 1871-72, approximately 2 miles north of Port Chester, New York, he built what has been termed the first reinforced concrete structure in America--a residence entirely of "beton in combination with iron."

Progress in the twentieth century has been marked by the emergence of reinforced concrete as a prime construction material. When first used it was hidden from view by facings and artificialities, and at a later date it was merely used to ape the older building materials, brick and stone. Modern architecture is getting away from these practices, however, and concrete is being brought out into the open where its individuality is gradually being expressed. We are accustomed to calling the twentieth century the "Steel Age," but perhaps the "Newest Stone Age" might turn out to be more appropriate. The relative success with which reinforced concrete structures have been able to resist bomb blast may add further to its desirability as the material of the future. The great steelmaker, Andrew Carnegie, payed the following complement to concrete at a conference in Washington

on the conservation of the natural resources of the United States:- "The use of concrete, simple and reinforced, is already reducing the consumption of structural steel. The materials for cement and concrete abound in every part of the country, and while the arts of making and using them are still in their infancy, the products promise to become superior to steel and stone in strength, durability and convenience, and economy and use."

The first extensive use of iron in buildings was made by the Romans, on such a scale that the importance of their work was not exceeded until the nineteenth century.

Iron and Steel

ANCIENT USAGE OF IRON -- Although the extensive use of iron in building construction is a comparatively modern development, the use of iron for weapons and tools dates back to prehistoric times. Just where the art of smelting iron from its ore originated is indefinite, but many writers have suggested that it arose in China and India and was then communicated to Mesopotamia and Egypt. Its first use as a structural material seems to have been in Babylonia where, by the time of Nebuchadnezzar in the sixth century B.C., it had displaced bronze in stone-bridge cramps and in bolts used for barring and hanging gates. The British Museum has in its possession one of the earliest pieces of iron used on a building--a great iron bolt which formerly barred one of the bronze gates at Nineveh (destroyed 606 B.C.). The use of iron as a building material in Egypt seems to have come later--with the Ptolemies and Romans--although Sir Flinders

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Petrie reported the find of a definite lump of iron wrapped up with copper axes whose form and corresponding level in the foundations of the Abydos temples marked them as Sixth Dynasty

of enclosing obelisks or chapels with iron grilles developed in

products, some four thousand years old. However, iron was of little importance in early Egyptian building construction. The Cretans and Greeks made use of bronze for decorative purposes, but we have little evidence of their use of iron for this purpose. No remains of their architectural ironwork has been found, but written evidence exists that they knew casting, embossing, forging, inlaying, polishing, tempering, and welding of iron.

The first extensive use of iron in buildings was made by the Romans, on such a scale that the volume and importance of their work was not exceeded until the nineteenth century. Vitruvius recommended a system for installing the ceilings of the hot baths which called for an extensive use of iron. In this method, iron rods or arcs 2 feet apart, suspended by iron hooks from an upper framing of timber, supported ceiling tiles fixed between them. The third century Baths of Caracalla have even revealed the use of the T-iron girder. In lighter work iron was used for window bars, casement windows, grilles or railings of amphitheatres, and gates of the fora.

ARCHITECTURAL USE OF IRON PRIOR TO THE 19th CENTURY -- Iron dropped in importance in Byzantine buildings, but it still served many useful purposes. Metal collars at the ends of marble shafts were often used, as were iron tie rods to strengthen arches--as at St. Mark's at Venice. During the Romanesque period when many churches were the last stronghold against marauding barbarians, heavily armored doors were not uncommon. Especially was this true of the Saxon churches of England until the Norman invasion. During the twelfth century the practice of enclosing chancels or chapels with iron grilles developed in

order to protect the treasuries of the churches and cathedrals. One such early example was found at Le Puy, France, in the form of fragments of St. Swithin's grille (c 1093). Although the chief medieval expression came in stone, there were craftsmen able to fashion iron decorative work as well. The hinges of the doors of Notre Dame in Paris, for example, were of such beauty and delicacy that their authorship was often attributed to the devil. In the fourteenth century geometrical designs began appearing in the church grilles as a result of the influence of the East.

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In his "Four Books on Architecture" Palladio noted that sixteenth century iron was "fit to make cramps, spikes, nails, hinges, bolts, chains, locks, and the like works." No important ironwork in architecture appeared during the greater part of the sixteenth and seventeenth centuries--if we exclude Venice, which abounded in beautiful sixteenth century lace-like ironwork, and other scattered centers of the art. Church construction was relegated to a relatively minor role and a lighter work appeared for dwelling places. In 1689 Jean Tijou arrived in England in the train of William of Orange with a new method of treating decorative ironwork. He is probably best remembered for his ironwork at St. Paul's which was carried out from 1691 onwards. After the middle of the eighteenth century ironwork began to decline once more, for the Roman rules for masonry, so popular at the time, had practically nothing to do with ironwork. The graceful scrolls of the smiths gave way to a heavier and more rigid type of design, and decorative ironwork came to an end in the early nineteenth century. Structurally, ironwork had

hardly begun; iron had been used slightly in the Salisbury Cathedral, in the Duomo at Florence, and in the dome of St. Paul's, but in none had it been a major structural feature.

IRON MANUFACTURE -- In all probability the first smelting of iron ore was an accident which took place in an open heap of burning wood or charcoal. Once the process had been recognized for what it was, attempts to overcome the wastefulness and tediousness must naturally have led to the invention of a furnace. It is not unlikely that the early furnaces resembled the low conical types used by some of the African tribes found by Dr. Livingstone in the nineteenth century. In these, air was admitted through openings at the lower end of the cone while charcoal was introduced at the upper end. During the course of evolution of the furnace, temperatures were raised by the use of hand bellows, then foot-blast, and afterwards the water-blast (as used in the Catalan forge). The Catalan forge seems to have originated some four or five centuries ago in Spain and in France. It was a small piece of equipment, the working hearth being only a little over 1 foot square. The hearth was heaped with a mixture of crushed ore and charcoal, and once in about six hours a mass of reduced iron and slag was removed from the furnace and dragged to the tilt hammer to be shaped.

It came to be realized in the Middle Ages that molten metal could be tapped and could be used in making castings. As early as 1377 cannons of iron were cast at Erfert, Germany, when Frankfurt ordered one capable of throwing 1000-pound balls. The earliest of the great cannon were usually of wrought iron,

the iron staves being held together like a cask by strong iron rings, but these were soon superseded by those of cast bronze and cast iron. Examples of fifteenth century cast-iron cannons may still be seen in the German Museum at Nuremberg and in the arsenal at Morat, Switzerland. From the latter part of the Middle Ages the iron trade, largely because of its relationship to the cannon, was encouraged by governments and continued to expand.

Expansion depended, of course, on many factors, not the least of which was fuel. Traditionally, from earliest times, wood had been the basic fuel. Pliny held that for smelting iron and copper, pine wood was best, but he also considered Egyptian papyrus good for the purpose. England, like most of the other western countries, encouraged the production of iron for many years until the destruction of timber in the southern counties came to be looked upon as a national calamity. In 1581 Parliament passed an Act which prohibited, among other things, the conversion of wood into fuel for the making of iron within 14 miles of the Thames. At the time, the burning of coal in private dwellings was looked upon as unhealthy, and the people of London did not relish the thought of cold winters without an ample supply of wood. Not only was there a popular prejudice against the use of coal in the home, but old iron-makers, wise in their trade, insisted that only charcoal of wood could reduce ore properly. Nevertheless, the rapid disappearance of the forests, with or without legislation, drove the manufacturers to investigate other fuel possibilities.

First to take out an English patent for the reduction of ore by coal was Simon Sturtevant, a German mining expert, who proposed

"to neale, melt, and worke all kind of metal cares, irons, and steeles with sea-coale, pit coale, earth-coale, and brush fewell." His process was not successful on a large scale but it encouraged and was closely followed by other patents along the same lines. Practical success in smelting iron with a fuel made from pit-coal was achieved shortly thereafter by Dud Dudley (1599-1684) at Pensnet in Worcestershire, and was described in the patent taken out in the name of his father, Lord Dudley, in 1620. Dudley's invention was born before its time, however, and it was not until the establishment of the Coalbrookdale Iron Works in Shropshire by Abraham Darby early in the eighteenth century that the smelting of iron by means of coke and coal was first adopted on a large scale as the regular method of manufacture. When Darby first set up his trade in Coalbrookdale (1709) it appears that his sole fuel was charcoal, but before his death in 1717 his favorite charge for the furnaces had developed into five baskets of coke, two of brays, (small coke) and one of peat; next followed by the ore, and then one of limestone. As the art of smelting with coke improved--along with the increased power of the blast furnace--the use of charcoal was gradually discontinued and finally given up altogether.

Furnaces in the eighteenth century continued to be small; in 1740 the average output from each furnace in Great Britain was less than a ton a day. ²³ In the space of a hundred years that figure had increased to 15 tons a day, mainly because of the improvements which had occurred in the blast furnace. The increased demand for iron brought about an increased interest in coal-mining. This, in turn, stimulated pump development for

the charge to be melted. Watt's steam engine, which was made possible by the development of iron, not only acted as a further step in solving the pumping problem but also acted to displace water power in the furnishing of large amounts of air to the blast furnaces. Thus the interchange of inventions and needs acted to bring about the production of iron on a larger scale than ever before. Since 1845 the blast furnace increased in size, capacity, and temperature to such an extent that average daily production per furnace in the United States in 1940 was 637 tons, some furnaces even exceeding 1000 tons.

Until the latter part of the eighteenth century the common methods of making iron were to cast it or to hammer heated cast iron into the desired shapes. In casting, the iron was run into a main furrow and side furrows made in sand; larger lengths were called "sows" and the smaller lengths "pigs." When heated again the pigs became malleable and were then subjected to the hammer. The manufacturing and shaping of the metal had gone through many stages by the time Henry Cort of Fontley, England, took out two patents which played such an important part in the subsequent development of wrought iron. In 1783 he patented the scheme of reducing faggots of piled iron into bars and the welding of such bars by rollers instead of by forge-hammers. In the following year he patented a greatly improved process over that originated by the Craneges brothers (1766) and modified by Peter Onions (1783) for the production of wrought from pig iron. Essentially it consisted of using an "open hearth" or "reverberatory" furnace in which the flames, deflected by the roof, swirled over and around the iron.

the charge to be melted. In this manner the iron could be worked or "puddled" by hand without coming into contact with the fuel. With certain improvements his two processes have remained in use to this day. The large amount of hand labor necessary in the "puddling" process was reduced by James Aston in 1925 when he introduced a new, and essentially mechanical, method for producing wrought iron in large units.

STEEL MANUFACTURE -- Long before it was realized that carbon was the hardening agent, the material we now call steel was known as a special form of iron which could be forged at a red heat and which became hard when plunged into water while still at a bright red heat. Its origin goes well back before the Christian era; just how far back is uncertain, but we do know that the Chalybes on the southern shore of the Pontus Euxinus gained a reputation in Classical times as great iron and steel makers.²⁴ As the centuries passed some few standard methods of steel manufacture slowly developed and were passed on from generation to generation. Little definite is known as to when experiment passed into standard practice. Conversion of bar iron into steel by dipping it into other fused iron and allowing it to remain there for several hours was mentioned by Georgius Agricola in "De Re Metallica" (1556) as being a process well-known and practiced in his time. The eighteenth century French scientist and inventor René de Réaumur described the making of cement or blister steel as a well-developed industry in 1722. In this process wrought-iron bars were heated in a furnace with charcoal bars between and around them. Some carbon was, therefore, transferred to the

iron where the charcoal and iron had remained in contact. Obviously the only way to render blister steel homogeneous was to remelt it, cast, and roll again--a method perfected by Benjamin Huntsman, of Attercliffe, near Sheffield. His cast or crucible steel was in commercial production prior to 1770.

Prior to the second half of the nineteenth century industry had its choice of brittle cast iron, largely produced by laborious "puddling"; and steel, which could be produced only in such small quantities that its use was restricted to edge tools and small machine parts. In his "Autobiography" (London, 1905) Henry Bessemer indicated the painfully slow manufacturing process by which steel was made prior to the introduction of his famous converter. After being transformed from pig to wrought iron by puddling, the bars were heated for six weeks in contact with charcoal. Following this treatment the bars were broken into small pieces and melted in crucibles which yielded only very small castings. Bessemer set himself the task of producing a metal having characteristics comparable with those of wrought iron or steel and yet capable of being run into a large mold in a fluid condition. He not only accomplished this with his converter, but he also cut down the time of manufacture to a fraction of what it had been before. His process consisted of simply introducing atmospheric air into a cylindrical chamber through tuyeres and blowing the air through the molten mass of iron in the chamber. In a half hour the temperature of the mass was raised and the carbon and silicon were removed, all without skilled manipulation. By allowing the reaction to go to the end he produced wholly decarburized malleable iron. By stopping

the reaction he could vary the amount of carbon remaining and hence, could control the quality of the iron or mild steel. The success of his invention was signaled in 1856 by the production of two 10-inch square ingots which were rolled into flat-footed rails at the Dowlais Iron Works in Wales. In the same year his process became known to the world when he described it before the British Association at Cheltenham. The process was not a commercial success at first, for the ordinary pig iron used in bar making contained too much phosphorus--a point which Bessemer had not noted in his original discovery when he had used a different pig iron. The main difficulties were soon overcome, however, and commercial production commenced in 1858 when Bessemer installed his works at Sheffield.

In the same year that Bessemer introduced his converter (1856) Frederick Siemens patented a gas producer and regenerative furnace. The significance of this invention was realized in 1865 when his brother Charles William Siemens and Pierre Martin patented what was essentially a puddling process for steel, since known as the Siemens-Martin or "open hearth" process. In this method the temperature--because of the gas producer and regenerative system of firing--was raised so high that iron could be kept molten throughout the process, and the bath was stirred by the evolution of carbon monoxide resulting from the additions of iron oxide. Experimental steel was produced by Martin at Siereuil, France, in 1865 and by Siemens at Birmingham, England in 1867. The process was put on a regular commercial basis in 1869 with the setting up of the Siemens' works at Landore, South Wales. Siemens steel was readily adopted in the industry, for

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it was found to be freer of bubbles and flaws than was the Bessemer product. A further step was taken in 1878 when Thomas and Gilchrist developed a process for the removal of phosphorus by adding lime to the slag to make it basic. Since that time most of the steel in the world has been made by either the Bessemer or the open hearth process (both acid or basic), although the electric furnace has been gaining in popularity in the twentieth century. Most of the steel in the United States, the world's largest producer, is now made by the basic open hearth process. It has gained preference over the originally adopted acid-Bessemer system for the following reasons: the basic open hearth (1) can start with a stock of any percentage of phosphorus, whereas the Bessemer is limited; (2) can use scrap steel in almost any quantity; (3) permits more thorough de-oxidation of the metal. The effect of this large-scale production of steel was soon reflected in the latter part of the nineteenth century by the introduction of steel structural shapes which brought about a revolution in large building construction.

SKYSCRAPERS -- The basic principle of the metal-framed building was enunciated by the French architect Eugène Viollet-le-Duc (1814-79) long before the modern "skyscraper" was born, but there is no evidence that he ever made any attempt to put his idea into practice. A forerunner of the present-day building skeleton--the Crystal Palace of iron and glass--was erected by Paxton for the London Exhibition of 1851, but it was looked upon largely as a curiosity and had little influence on subsequent construction practice. In 1880 L.S. Buffington, an

architect of Minneapolis, came across Viollet-le Duc's suggestion and began visualizing iron framed structures of twenty-five or thirty stories--almost twice as high as any building then standing. He called these structures "cloud-scrappers," patenting the idea in 1887-88. Before Buffington took out his patent though, the idea had become a reality. In 1884 William L. Jenny, a Chicago architect, designed the ten-story Home Insurance Building, the first building on record to rely for its structural strength upon a complete skeleton frame of iron, erected independently and afterwards enclosed in masonry. The original specifications called for wrought iron throughout, but the contractors, the Carnegie-Phipps Company of Pittsburg, obtained permission to replace the wrought iron with Bessemer steel in the four uppermost stories. Two stories were later added to the building in 1890, and in 1931 it was pulled down to make room for a larger structure.

In the early years of this type of construction cast iron was sometimes used in compression, but after the collapse of the thirteen story Darlington Apartment House of New York in 1904, it was never used again (although it was not shown that cast iron had caused the failure). It was also customary in the early buildings to use masonry walls as auxillary supports. A departure from this custom occurred in Chicago's Tacoma Building (1887) where, for the first time, the outer walls were mere curtains hung on steel frames. Shortly thereafter Jenny designed the Leiter Building, the first without a single self-supporting wall, external or internal. A fashion in framework was set by the Rand McNally Building (1889) in Chicago where the skeleton was

made of rolled-steel beams and columns built up of standard bridge-steel shapes riveted together.

Thus far the discussion has been confined to buildings of Chicago, but to the world, New York--which prior to World War II had forty buildings over 500 feet and two of them over a 1000--symbolizes twentieth century fashion in large steel-framed structures. New York's first skyscraper, B.L. Gilbert's 200-foot Tower Building, was erected in 1889 but was demolished to make way for a larger one in 1914. History was made in 1893 with the erection of Manhattan Life Insurance Building, whose seventeen stories and tower reaching to 344 feet topped what had been the apex of the city for over half a century, the top of the Trinity Church steeple (284 feet). The scarcity and value of ground and the need for more working space brought larger and larger buildings whose growth was unhampered by building restrictions in the early years. Last of the large buildings to be erected before the 1916 zoning laws went into effect was the 792-foot Woolworth Building in 1913. Briefly, the laws called for the stepping back of a building a specified amount at certain heights, according to the width of the street on which the side abutted. This stepping back applied to only three-quarters of the area of a building; the remaining quarter of the area could be surmounted by vertical construction to any desired height.

Although these laws helped to admit more light and air to the streets, they in no way prevented taller buildings. First of the large structures to surpass the 984 feet of the Eiffel Tower was the 1046-foot Chrysler Building. It, in turn, was soon passed by the Empire State Building, the loftiest structure

yet built anywhere in the world. Work was begun in 1929 and offices were opened in 1931, a period of slightly under a year having been consumed in actually making the building. Starrett Brothers and Eken, the contractors, employed a working force which ranged from 2500 to 4000 men during the construction period. For the foundation a steel grillage was placed on two-hundred reinforced concrete cylinders, each 10 feet in diameter and capable of standing up to a load of 10,000,000 pounds. These pillars went to bedrock 30 to 40 feet below basement level. The skeleton of the building was erected at a rate of four and one-half stories a week, and the stonework advanced, at times, one story a day. When finally completed, the structure had attained a height of 1250 feet, made up of the 1045-foot lower section of eighty-six stories, plus a secondary tower of 205 feet. In addition, a small mast of 15½ feet carrying instruments was installed at the top. A total of nearly 70 acres of floor space had been created on a 2-acre plot of ground. Plans have been made for even greater buildings, but the problem has been financial, not constructional.

Just what the metal-framed building has meant in the construction field is probably better realized by noting what had been done with the previously traditional materials. The tallest commercial building of masonry ever built was Chicago's 16-storied Nomadnock Building whose basement walls were 15 feet thick. In America's capital the Washington Monument--an almost solid stone obelisk--stands as the tallest structure in stone in the world, 555 feet from the ground to the aluminum cap which surmounts it. Thus we see that steel has not only changed the old concept of building everything solidly from the ground up, but it has also

made possible the large concentration of working space on a small area of land by freeing the limit in height imposed by other materials. In so doing, it has developed a new type of architecture distinct from any of that of the past.

Roofing, Glazing, and Testing

ROOF COVERINGS -- We have previously noted that in Egypt the roofs of the temples were usually made of huge flat slabs of stone, and in the lesser buildings a flat mud roof was placed on a ceiling of date palm trunks laid close together. Similar roofing was also used in Assyria, Persia, and primitive Greece. Long before Pericles, tiles of marble or terra cotta were used on the sloping roofs of Greek temples and other important structures. The large slabs of marble were usually placed on an open framework of timber, and narrow ridged tiles acted to cover the vertical joints. At the Temple of Apollo at Bassae tiles were found measuring 3 feet 6 inches by 2 feet $1\frac{1}{2}$ inches by 1 foot 6 inches. The Romans closely followed the Greeks in the use of marble and terra cotta tiles. Among the various kinds of tile found in Roman England was an oblong type of coarse red pottery measuring 17 by 14 by approximately 1 inch, with flanges along the longer edges. Half-rounds were then placed over the flanges of two adjacent tiles to make the roof secure against water. They also made use of metals as exemplified by the copper plates on the Pantheon and lead on a temple in Auvergne. Lead was also used in Byzantine work for the covering of domes like Constantine's Basilica of the Holy Sepulchre at Jerusalem. We find,

in addition, timber roofs covered with half-round Italian tiles.

The half-round tiles continued popular in the Romanesque period, although roofs were occasionally covered with metal plates. Many churches in Saxon times and in the Middle Ages especially were covered with lead. The Venerable Bede reported that at the church at Lindisfarne (638) the bishop "took off the thatch and covered it, both walls and roof, with lead." The Choir of Canterbury (1093-1130) was one of the earliest of the great medieval structures to be roofed with lead, a practice that flourished in church construction from the thirteenth to the sixteenth century. Lead of this period was cast in thick sheets, weighing 12 to 13 pounds per square foot, on smooth sand specially prepared for each sheet. It contained much silver and arsenic which accounted for the beautiful white "patina" appearing on it with age. Slates and tiles with nibs joined lead as a favorite covering during Gothic times, and thatch, of course, remained popular for smaller dwellings. In the Orient and in Spain colored glazed tiles achieved a great popularity, and stone ashlar roofs came to be used extensively in England. These materials, continued in favor almost exclusively until the nineteenth century when new techniques and processes brought a multitude of covering materials, many designed to go directly over wood or concrete. Iron painted roofs became common in Russia and copper roofs were erected with increasing frequency. Today corrugated iron and steel sheets, slag and gravel, various forms of asphalt, and wooden shingles are but a few of the materials which have joined the older types of roofing still in use in many parts of the world.

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GLAZING -- Although structural glass for windows, walls, and partitions is a most recent development, the use of non-structural glass for windows dates back to the Romans. Pliny said that glass-making began in Syria and that glass makers were imported to Egypt in the Eighteenth Dynasty, but we have no evidence that they made windows. The so-called "windows" in the clerestory of the Hypostyle Hall at Karnak were really great stone grilles to admit light in small patches, but they were unglazed. Glass for windows seems to have appeared in the first century of the Christian era, for Caligula (A.D. 37-41) provided his palace with glazed windows. Numerous examples of Roman glass have been found in Britain and elsewhere. It appears to have been cast in small sheets, fairly clear and of a greenish tint, in thicknesses ranging from $1/8$ to $2/5$ of an inch. One specimen found was a glazed sheet without bars measuring 2 feet 8 inches by 3 feet 8 inches. The glass was generally cemented or fixed with nuts and screws in frames made of bronze, copper, lead, or wood.

Glass was still being made in France in the fifth century, but as the Dark Ages closed in, the art became lost to the West. A small revival was begun in the seventh century when Greek glaziers were imported into France, and in 675 Benedict Bescop sent to France for glassmakers in order to glaze the windows of his church and monastery at Wearmouth. The windows which characterized the Anglo-Saxon churches were small for various reasons, among them being the scarcity of glass, the difficulty of glazing wide windows, and the fact that the church still served as a refuge on occasion. With each succeeding period glass windows became larger and larger, until today it is not uncommon to find houses with window openings in an average dwelling large

enough to walk through. Colored glass appeared in the West about the time of Charlemagne, having been previously known in the East. By the fourteenth century stained glass was of great importance in the churches, and in the fifteenth century the leading became subservient to the "picture" instead of defining and limiting the design. Apart from their use in churches, glass windows were by no means general in the sixteenth century, however, and were regarded in the eyes of the law as "movable furniture." Bay windows began to appear about this time and in the seventeenth century sash windows came to be known. Though the word "sash" is derived from the French "chassis" (frame) it seems that the French borrowed the idea from the English. Among the earliest of the sash windows were those employed in Inigo Jones's houses Raynham (1630-36) and Colehill (1650). At first only the lower part of the sash was movable, being kept up by a series of notches and a catch to hook into them, but late in the century the modern method of weights, pulleys, and cords was introduced--probably from Holland. Since that time the greatest advance in glass from the builder's viewpoint has been the introduction of the structural glass block in the twentieth century, but its use to date has been relatively limited and it is yet too early to predict what effect it will have on building practice of the future.

MATERIALS TESTING -- Strictly speaking, even the earliest builders were strength of materials testers, for they performed their tests with actual structures. If a structure fell down in the process of building, the material was too weak for the

way in which it had been used; so they built again with a greater size of the same material, or with a different material, or in a different manner until the structure stayed up. It is probable that such structural engineers as the Romans pre-tested materials in order to predict their future action under load when part of a structure, but we have no direct evidence of this. The first on record to scientifically test materials was the Italian astronomer Galileo Galilei (1564-1642). In the second dialogue of his "Discourse e Dimostrazioni matematiche" (Leiden, 1638) he gave several propositions with regard to fractures of rods, beams, and hollow cylinders. He wrongly assumed that the fibres in a strained beam are inextensible, but for all its errors the work was a significant contribution. It not only gave the impulse but also determined the direction of all inquiries concerning rupture and the strength of beams which were studied in the next century. The next investigator of note was Robert Hooke (1635-1702), formulator of the modern conception of elasticity. In his "De potentia restitutiva" (London, 1678) he stated that eighteen years before he had first found out the theory of springs (any springy body whatever), but he had not published it then for he wanted to patent a particular application of it. His work was followed by that of Mariotte (1620?-1684) who seems to have been the first investigator to apply anything corresponding to the elasticity of Hooke to the fibres of the beam in Galileo's problem. In "Traité du mouvement des eaux" (Paris, 1686) he published the results of his experiments of 1680 which showed Galileo to have been wrong. Mariotte showed that some fibers are compressed and others are extended, and he stated,

without proof, that half of the fibers are compressed and the other half extended. The first work of genuine mathematical value on the subject was that produced by James Bernoulli (1654-1705), who solved the problem of the elastic curve. In the eighteenth century many more mathematicians followed the lead of Bernoulli, notable among them being his nephew Daniel Bernoulli, Parent, Euler, Coulomb, and Girard (writer of the first practical treatise on elasticity, Paris 1798).

The nineteenth century opened with a continuation of the work of the theoretical mathematicians. In "A Course of Lectures on Natural Philosophy and the Mechanical Arts" (London, 1807) Thomas Young (1773-1829) mentioned a constant of elasticity since referred to as "Young's modulus." His definition in this work did not agree with what we now term Young's modulus, however. He was followed by many whose names have since become familiar to every engineer: Poisson, Saint-Venant, Rankine, and Kirchoff, to mention but a few. Throughout the century French, German, and English investigators dominated the field. During the two decades from 1840 to 1860 a new feature was quite apparent in the "Proceedings" of both the Civil and Mechanical Engineers-- the report of a great many "practical" tests of cast and wrought iron, brought about primarily through the problems raised by bridge structures and gun-making. The practical testing method has carried over into the twentieth century, supplemented by mathematical principles whose roots go back through the centuries. Today, every structure designed is based on the results of materials testing, resulting in a saving of time, labor, and materials never dreamed of by the great engineers of the Classical,

Medieval, or even Early Modern times.

Summary

Until the nineteenth century, construction was carried out almost exclusively with the traditional materials, wood, brick, and stone. The early Egyptians are remembered particularly for their use of stone in the giant pyramids and in their massive temples where post and lintel construction predominated. The scarcity of trees in their country prevented the Egyptians from using wood extensively, but the annual inundations provided an ample amount of mud which was used for "wattle and daub" and for sun-dried bricks. Sun-dried and kiln-dried bricks seem to have been the main building materials of the Mesopotamians, and for that reason few of their structures have withstood the test of centuries. Their structural use of stone seems to have been limited chiefly to lower facings, so we do not find the great use of the heavy lintel in their construction. The lintel appeared once more in the Cyclopean masonry of the pre-Hellenic Greeks, but it was a massive and unweildly sort of architecture.

With the Hellenic Greeks a perfect correlation of architecture, sculpture, and painting was achieved. Classic grace was given to their temples of stone which have survived to this day. Once more the post and lintel was the dominating structural feature, but it was light and pleasing where its Egyptian and Mycenaean predecessors had been massive and overpowering. The Romans combined this structural principle with the semi-circular arch which they had inherited from the Etruscans. They were

prolific builders in stone, brick, and "concrete," and they made extensive use of wood as well. Their ability to make a building cement which was not equaled until the nineteenth century accounted for their tremendous success in the structural field. Where civilizations before them had confined their architectural efforts to one or two types such as temples or palaces, the Romans extended these efforts to almost every phase of public life.

Before Rome had perished a new culture was forming in the East radiating out from Byzantium. Here we find the most striking structural feature to be the dome of brick and mortar, based somewhat on the Roman tradition of construction. In the West, Roman tradition persisted in the semi-circular arch, but as the Dark Ages descended, much of the old constructional skill was lost and building standards were lowered. During the Romanesque period practically all of the construction work of any size was ecclesiastical, and in the eleventh and twelfth centuries, especially, most of the work done was due almost entirely to the monastic orders. In the latter part of the twelfth century the Gothic order began to emerge, being strongest in France and England. Here was the richest expression in stone yet seen, an expression which dominated the architecture of the West until the sixteenth century. The classical semi-circular arch gave way to the pointed or broken arch and verticality received the emphasis. Again, work of any consequence was almost always ecclesiastical. Not only was stone exercised to its limit, but the wooden roof truss began to appear in many beautiful forms. Fully three-quarters of a medieval building was a mason's work, so it is

was enlivened in the works of the Italian architects, particularly

not surprising to find that the engineer or architect in charge of the building of one of these great medieval structures had not only been trained as a mason but also worked with his hands on the structure himself. This did not prevent his acquiring an intimate knowledge of draughting if we may judge from the full record of excellent thirteenth century drawings by Villard de Honnecourt, still preserved at the Bibliothèque Nationale in Paris.

For the most part the architect of the Middle Ages remained anonymous, but with the rise of the Renaissance in Italy in the latter fourteenth century the comparative anonymity of the architect ceased. In general, he was a man of many parts, being a painter, sculptor, mathematician, and many other things, as well as an architect and engineer. Many illustrious names and their works come to mind when one speaks of construction in this period: Brunelleschi (1377-1446) and the Pitti palace in Florence, Alberti (1404-72) and the Church of S. Andrea at Mantua, Bramante (1444-1514) and the Chancellaria palace at Rome, to mention but a few. The building of the greatest and most remarkable structure of the Renaissance, St. Peter's in Rome, was supervised by many famous architects who, oddly enough, are generally remembered more for their painting ability than for their engineering; the list includes such men as Rossellino (1409-63), Bramante, Raphael (1483-1520), Peruzzi (1481-1536), Antonio Sangallo (1485-1546), Michelangelo (1475-1564), and Maderno (1556-1629).

The invention of the printing press (1453) helped to popularize the classical literature from which the Renaissance drew much of its inspiration. Vitruvius, re-discovered about 1452, was eulogized in the works of the Italian architects, Palladio

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(1518-80) and Vignola (1507-73), with the result that the Greek and Roman "Orders" began to appear once more. The post and lintel, exterior columns, semi-circular arches, and hemispherical domes became signs of the times. From Italy the movement spread to France and then to Germany, the Low Countries, and England. With the new rules laid down for construction came the professional architect to replace the old master-mason. One of the first professional architects in France, Philibert de L'Orme (1515-70), is remembered particularly for his writings of some importance on architectural Orders and construction and for his invention of a new type of built-up timber roof truss. A struggle between Classic and Gothic asserted itself in the sixteenth century, especially in France, with the result that Gothic largely disappeared in the new construction of the seventeenth century. What St. Peter's had been to Renaissance Italy, the Louvre--numbering among its architects Lescoq (1510-78), Lemercier (1590-1654), Levau (1612-70), and Perrault (1613-88)--was to Renaissance France. In England the rebirth in construction was symbolized by the Banqueting House at Whitehall by Inigo Jones (1573-1652). His work in England was later followed by that of such illustrious architects as Sir Christopher Wren (1632-1723) and Nicholas Hawksmoor (1661-1736).

The freshness of ideas gradually wore off, however, and architecture in the eighteenth century developed an artificiality which was largely an affair of rules. Books on building construction, architectural Orders, and monumental designs poured forth, some written by comparatively uneducated men and others by gilded aristocrats who had taken the "Grand Tour"

and had made the Orders their bible. A low ebb was probably reached in the nineteenth century when various "revivals" took place, none of them with any real roots in the age they were representing. Many authorities have held that the large-scale structures of this period simply reflected the conventionality, self-sufficiency, and pompous and complacent materialism of the times. While there is no doubt some element of truth in this assertion, it must also be remembered that this was the century which saw the introduction of Portland cement and concrete, and iron and steel as structural materials. At first, constructors endeavored to imitate the traditional materials with the new ones, designing structures, therefore, not altogether reflecting the characteristics of the component materials. A frequent device used was the disguising of a new material as an old, such as metal as wood. It was not until the latter part of the century that structural steel became a commercial possibility and hence, a main factor in building construction. In the eighties the first of the steel skeleton "skyscrapers" appeared, but it was not until the twentieth century was well under way that the metal-framed building began to assume a character all of its own. The twentieth century also claims reinforced concrete as another material which got its start in the previous century but which has only lately come to reveal its true characteristics in construction.

Materials of the future will ultimately determine what direction building construction takes, as has been the case in the past. Yesterday's emphasis was on durability and show; today's emphasis is on speed and ease of construction; perhaps tomorrow's

emphasis will be on security. Events since the close of World War II have not convinced men that war has been forever banished from the earth, with the result that many structures are once more being constructed underground. Will this in fact breed a new type of construction, or will it simply signalize the completion of a cycle--the return of man to the cavern and Stone Age? If the world's differences can be resolved without resort to what may well be Armageddon, future construction will undoubtedly take a different turn. Durability, speed and ease of construction, and beauty will all be high-priority factors. Perhaps the old square-edged buildings, so shaped from the beginning of time because of the limitations of the materials used, will give way to more rounded types, made possible by the introduction of more plastic materials. Whatever the shape of things to come, both in the political and construction fields, the builder will find his talents still needed in the hustle-bustle of the commercial world, in the crazy panic of war, or after all the tumult and shouting have died away.

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Chapter III

ROADS

that an amber route between Denmark and northern Italy existed
in this period (2000-). Pre-Roman Roads

Though not specifically connected with the amber routes,

ORIGIN -- Before the dawn of recorded history roads made their first appearance as small trails made by game and hunters. Many theories have been advanced as to how these trails developed into well-marked thoroughfares, the most popular theory being that of the path of the wild animal. It is argued that wild animals would in time beat suitable paths to watering places, and that hunters would follow these paths as the line of least resistance. ¹ Roe, however, in "The Wild Animal Path of Origin of Ancient Roads" (Antiquity III, 1929) argues strongly against this view, as the results of his observations have shown that there was no connection between the bison paths and the paths of the first trap-²pers and traders in North America. Forbes in "Notes on the History of Ancient Roads and Their Construction," (Amsterdam, 1934) offers the view that hunters would choose their paths by referring to prominent land-marks, thus enabling them to return expeditiously to their camp on completion of the hunt. Undoubtedly each theory holds true for certain portions of the world, but it was not until man raised himself from a hand-to-mouth existence and began to long for luxuries which only travel would bring him that real road systems began to develop.

Knossos. This road was bordered by retaining walls and

PREHISTORIC TRADE ROUTES -- Amber, valued for its beauty, medical properties, and protection when worn as a charm, proved to be a motivating force in the establishment of long trade routes

in West Central Europe in the Early Bronze Age. Finds indicate that an amber route between Denmark and Northern Italy existed in this period (2000-1800 B.C.).

Though not specifically connected with the amber routes, evidences of the first artificial roads (not antedating 2500 B.C.) have been found in Northwestern Europe. These were log roads which were brought into their fullest development by the Dutch before 1500 B.C. This type of road was also known in Switzerland, possibly as early as 1800 B.C., as testified by the remains in the village of Federnsee. Further south the gem lapis lazuli, used for ornament and pigment, found in Egypt and Ur indicates that trade routes existed across Afghanistan, Persia, and Arabia possibly as early as 3000 B.C. It is believed that very early routes existed in China and India, but our information to date on that subject is very meagre.

ANCIENT ROADS OF MALTA AND CRETE -- The excavations carried on by Professor T. Zammit ("Prehistoric Malta." London, 1932) have been most helpful in tracing the story of the early road in Malta and in Crete. In Malta cart tracks were found probably dating back to the Megalithic Period (2000-1500 B.C.), and here also were found evidences of roads having been made of rammed earth and broken stone. Crete yielded a much greater find in what is probably the oldest road in Europe, the road from Kome to Knossos. This road was bordered by retaining walls made of rough hewn limestone blocks reaching a height of 8 feet or more. The road itself had a foundation course of stone blocks (2 to 8 inches) mounted in a clay gypsum mortar, over which lay a

2-inch loamy mortar, surmounted by a pavement of 2-inch basalt rock on the center portion and limestone lumps on the wings.

This road was part of an extensive system probably dating between 2600 and 2000 B.C., a system of straight roads similar to those of the Romans, centuries later.

ANCIENT EGYPTIAN ROADS -- A glance at the map of Egypt will show why the Egyptians never became great road builders despite the high state of their civilization. They had little reason to require roads for ordinary commercial enterprises because of the proximity of the Nile and various artificial canals. It is undoubtedly true that they built some roads to facilitate the movement of their stone blocks used in the pyramids, and other roads for removing ore from their gold mines. Herodotus (484-425 B.C.) tells us that a causeway of polished stone 5 furlongs long, 10 fathoms wide, and 8 fathoms high (at the highest point) was erected before the Great Pyramid of Cheops (c. 2900 B.C.). The road required ten years to build and quite rivaled in grandeur the pyramid itself, in the opinion of Herodotus. Rawlinson, the English translator of Herodotus, mentions the fact that the remains of a causeway still exist near the Great Pyramid, measuring (in 1875) about 1424 feet in length, 32 feet in breadth, and 85 feet at the highest point. Time undoubtedly has whittled down the length and breadth reported by Herodotus, but the greater modern height of the road indicates that an oversight was made by the historian or by his copyists. However, despite their other attainments in the engineering field the Egyptians really contributed little or nothing to the art

of roadbuilding.

EARLY ROADS IN MESOPOTAMIA AND PERSIA -- Earliest indications of improved roads in Mesopotamia come from bricks uncovered on a layer of sand bearing the inscription of Tukulti Ninurta I (1250 B.C.). Whether improved roads existed in the country prior to that time is open to question. Wheeled vehicles which would have furnished an incentive for good roads were not unknown in the early civilization which flourished in this area. Four-wheeled wagons were found in the "Queen's Grave" at Ur, dating back possibly to 3000 B.C., and some authors hold that the wheel was probably invented some five-hundred years earlier than that by the Sumerians. The first road engineers seem to have been the "unmani," army engineers in the service of Sargon II (c 720 B.C.). Their function was to make a one-track unpaved road ahead of the army to facilitate its advance, with the understanding that the road would only be used once. Still later, in the Late Babylonian Empire (700-540 B.C.), the art of paving made advances, but it appears to have been restricted largely to religious or processional streets. Most of the road building was accomplished under Nabopalazzar (625-605 B.C.) or under his son, Nebuchadnezzar (605-561 B.C.), the most famous work being the great processional road "Aiburshabu." It was over 1700 yards long, consisting of a foundation of three or more layers of brick in a bituminous mortar and a pavement of limestone slabs bordered by red and white breccia slabs. Such ordinary paved roads that existed at the time were made of brick layed in mastic. These contributions to the art of road making appear

to have been lost by subsequent civilizations. Although the Persians developed an extensive courier system to all parts of the empire under Darius Hystaspes (521-485 B.C.), we have no evidence to date of their improving and paving the roads. The art seems to have retrogressed, as a matter of fact, because they abandoned the use of bituminous mortar and employed wide courses of clay mortar.

EARLY ROADS OF INDIA -- Archaeology and literature have revealed little to date on the engineering of India and other countries of the Far East. In 1911 Mr. J. Marshall excavating at Bhitā found evidences of a road dating back to 800 B.C., made of a mixture of clay and broken potsherds pounded into a course of several inches and burnt in situ. Much later, the Mauryan Empire (300-150 B.C.) had a good network of roads built and maintained by a corps of road engineers known as the "sthapati." Although paved highways did not exist, the main town streets were paved with brick in the herringbone fashion and lesser roads had a beaten earth pavement. By the beginning of the Saka period (A.D. 75) the Indians had knowledge of stone slab and brick pavements, a type of concrete, and grouting with gypsum, lime or bitumen mortar, but it is doubtful that this knowledge accumulated over the centuries had any effect on simultaneous and subsequent road development in the West.

ROADS IN ANCIENT GREECE -- As with Egypt the character of the country did little to encourage the Greeks to become great road builders. Their long coast line encouraged water transportation

at all. That influence must have been very slight.

and their rugged mountains discouraged overland transportation, so they were for the most part a loosely federated group of city states. In the cities themselves little was done to improve the streets. Artificial ruts (ichnoi) were excavated in the roads for religious processions, being single-track at first and developing later into double tracks. The Cretan influence was felt in some parts, especially in Mycenaean Greece, and as early as 500 B.C. a "macadamized" road of chippings or broken stone placed on sub-soil and rammed (lithostratos) made its appearance. They even had some stone slab streets, but no effort was made to provide drainage until the Romans took charge in the first century B.C. While the Greeks did pass on their knowledge of macadam and lime mortar to the Romans, the Greek influence on and contribution to the road-making art may be regarded as negligible.

type of macadam following later. We know that the streets of

THE CONTRIBUTION OF CARTHAGE -- Many writers have stated that the Carthaginians were the first road builders, basing their argument primarily on the writings of Isidore of Seville (c A.D. 560-636), who noted in his "Originum sive entymologiarum" (Lib. XV, cap.16) that "---the Carthaginians are said to have been the first to pave roads with stones." Even if they had paved their roads, of which no other evidence archaeological or otherwise exists, it must be remembered that Carthage was at the height of her power around 275 B.C., a considerably later period than the periods of the civilizations mentioned above. No discoveries yet have revealed anything that was not already common to the Mediterranean countries, viz. tracks and a few slab paved streets. If the Carthaginians influenced the Roman road-makers at all, that influence must have been very slight.

DEVELOPMENT AND EXTENT -- The strength of Rome was due no less to her legions than to her extensive network of first-class roads, and to the Romans must be given the credit for being the first to develop the road as we understand it in a modern sense. To the military engineer the very construction of the major Roman roads indicates that they were not built primarily as military roads to facilitate the initial movement of the legions, but rather were administrative roads built after an area had been pacified, to enable the legions to carry out police missions as well as to aid communications and to foster trade.

The improvement of the early roads was, of course, a gradual development, cobbled paving appearing in the Bronze Age and a type of macadam following later. We know that the streets of Vetulonia were paved by 400 B.C. and possibly earlier. About 300 B.C. lime mortar was introduced from the cities of Magna Graecia and thus began the golden age of Roman road-building. In general, we may say that the road net of Italy was developed during the period 400 B.C. - A.D. 200, while the road system of the provinces was developed from 200 B.C. - A.D. 200.

The first of the great roads was the Via Appia, or Appian Way, begun in 312 B.C. under the consul Appius Claudius and extending south from Rome a distance of 120 miles to Capua. It was extended from time to time until it had reached Rhegium in the south-western extremity of Italy in 132 B.C. Begun shortly after the Appian Way was the Via Latina, also extending in a southerly direction from Rome. The first northerly road of any consequence

was the Via Flaminia begun under consul (or censor) C. Flaminius in 223 B.C. It extended from Rome to Ariminum and crossed the Apennines through a pass 800 meters high. It, too, was later extended as the Via Aemilia. Alpine passes were also developed, such as the Mt. Genève pass in the Cottian Alps, built in 75 B.C. connecting Milan to Arles. It was this pass that was used by Caesar in 58 B.C. on his way to the Gallic Wars.

The Roman roads in Britain have had considerable historic interest, for they well illustrate the Roman system of planning and construction and have played a large part in the subsequent development of the road system of the country. Of the four great Roman Ways the most famous is Watling Street, passing in a north-westerly direction from Dover to Canterbury, past London, to Chester and northern Wales, and thence to the coast. Ermine Street was the Great North Road in Roman times leaving London and passing through Huntingdon to Lincoln from which it extended to York. The most important of the cross-roads was the Fosse Way running in a north-easterly direction from Axminster in Devon through Bath and Leicester to Lincoln. Another important cross-road was the Icknield Way leaving from Suffolk in a south-westerly direction passing south of Cambridge and Oxford and connecting with roads of the southwest.

The Romans extended their roads into eleven regions, viz., Italy, Spain, Gaul, the British Isles, Illyria, Thrace, Asia Minor, Pontus, the East, Egypt and Africa, which were, in turn, divided into 113 provinces. The Itineraries of Antonius written during the reign of Diocletian (A.D. 284-305) indicated that twenty-nine military or major highways entered Rome alone, and

that there were in the Empire as a whole three hundred and seventy-two highways, covering a distance of approximately 53,000 Roman miles, or 50,000 English miles.

During the reign of Augustus (27 B.C. - A.D. 14) the *Cursus Publicus*, the government mail and courier service, was extended to the main roads of the Empire. Along the roads were set up stations to facilitate this service as well as to aid travellers. The major stations were known as "stativae" or "civitates," important places or cities. Next in importance were the "mansiones," located thirty or forty miles apart, where travellers could get provisions and a night's lodgings. The "mutationes" provided fresh horses and were located about ten or twelve miles apart.

TYPES OF ROADS -- Many different types of roads were built by the Romans depending upon the materials available and upon the uses to which the roads would be put. The major or military roads, which often served as processional routes in the neighborhood of Rome, were usually paved to a width of 16 Roman feet (15 feet 6 inches, English measure). Both sides of the paved portion were bounded by curbs 2 feet wide and 18 inches high, outside of which were gravelled "margines," each of a breadth half that of the paved portion. Thus the total breadth of one of these roads varied from 36 to 40 Roman feet. It is probable that the legions had the primary use of the paved portions, while ordinary travellers and animals were relegated to the "margines."

The ordinary roads could be placed in five classes. The

"Via" was the common road of a breadth of 8 feet, permitting carriages to pass one another without collision. The "Actus," so called from a common measure of land 4 feet by 120 feet, permitted the passage of one carriage. Horsemen and pedestrians could use the "Iter," 3 feet wide. Half the breadth of the "Iter" was the "Semita," and the "Calles" were simply mountain paths used by those tending flocks.

CONSTRUCTION -- Although Vitruvius, writing in the first century B.C., did not discuss road construction, he did mention paving in connection with building construction. Since many Roman roads have been found containing the same number of layers as he described, it became popular with later writers to describe road construction in his terms. Applying those terms to a typical Roman road, we would find four masonry layers placed over a "pavimentum," consisting of a bed of sand 4 to 6 inches thick or a bed of mortar 1 inch thick. Those layers in order of placing could be designated:

(1) "Statumen" - This might consist of flat or squared stones laid in cement or bound in clay with a usual thickness of 1 foot. Soil conditions determined this thickness, however, so that on a poor soil foundation the course might have a thickness of 2 feet, while on a rock foundation it would have zero thickness.

(2) "Rudus" or "ruderatio" - This layer would be a bed of concrete of about 8 or 10 inches in thickness, made of small stones or pebbles bound by a cement or clay and rammed hard.

(3) "Nucleus" - This also was a bed of concrete made of finer aggregate, gravel and sand. It varied in thickness from

about a foot to a foot and a half, and was laid down in successive layers and rolled. It appeared to be of very short radius.

(4) "Summum dorsum", "summa crusta" - The actual pavement varied from 8 to 12 inches in thickness, and was made of the best wearing material which was available in the vicinity. In Italy silex or lava polygonal blocks 1 to 3 feet in diameter, smooth on top and rough on the bottom were used. In other localities forge-cinders (viae ferreae), hard stones, and flint stones in cement found favor. In fact, in some localities, a preliminary curve. Thus we see that the Romans developed a road consisting essentially of a foundation, a binder, and a pavement. They paid particular attention to sub-soil conditions and drainage, and were not adverse to supporting their roads on piles when conditions warranted it. They excavated the road bed to reach firm ground where feasible. The thickness of their main roads generally varied from 3½ to 4 feet, very thick when compared with present day standards, and from this fact we may draw some interesting conclusions. Labor must have been plentiful and cheap, time was no object, and the engineers expected to have few maintenance problems with the completed roads. In this manner engineers and workers could devote their energies to expanding the Empire, rather than to merely maintaining the status quo. It is possible that they expected their roads to stand forever, and, as a matter of fact, some remained in good condition until the eighteenth century. During the eighteenth and nineteenth centuries many of these roads were dug up to provide material for roads and houses then under construction, and even today we may still see evidences of the original roads.

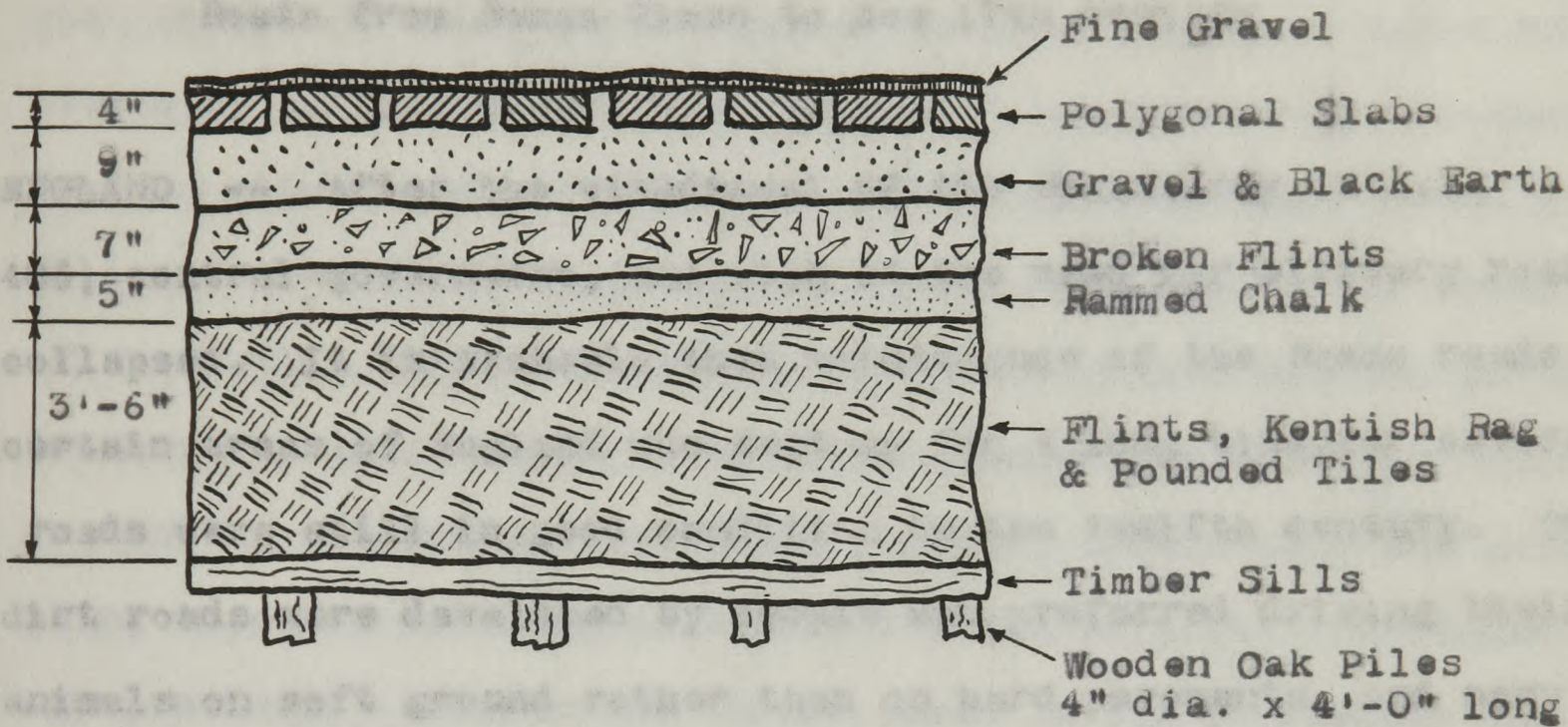
It has long been noted that curves were seldom used in Roman roads, and those that appeared were of very short radius. Above all, the Romans are noted for the directness of their roads, one good example being that of the Fosse Way, where in a distance of 200 miles between Axminster and Lincoln the maximum deviation from a straight line drawn between those two cities is 6 miles. Since surveying instruments were very crude at the time, it is possible that directness was obtained by the alignment of three or more sticks in the direction to be travelled, a preliminary survey having been made from hill to hill.

Roman roads were not always straight, but bogs and steep grades did not necessarily deter their course. Since only pack horses and small vehicles traversed these roads, grades up to 20 per cent were not uncommon. Because of their steep grades many of these Roman routes were abandoned by subsequent road builders. Another common characteristic of these roads, especially in Britain, is that they were usually elevated somewhat above the surrounding terrain, possibly to keep the legions in an advantageous position in case of surprise attack, or more likely to keep the roads free of snow in the winter.

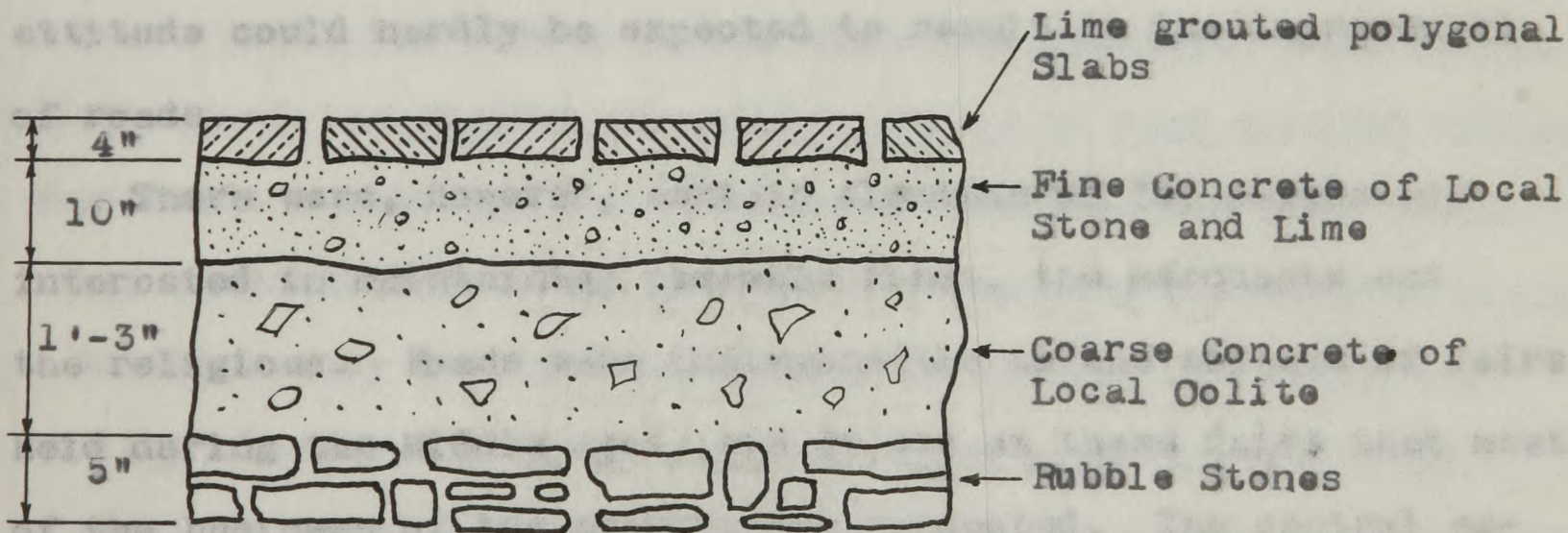
The fact that the Romans adopted a type of concrete mixture upon discovering that pozzolane made a good cement probably arrested for a long time the development of the more plastic types of construction such as cobbled or broken stone roads. It is probable that they did not use much pozzolano at any great distance from its Italian source, but they did use local materials in imitation of the pozzolano construction (i.e. lime in Britain). On the other hand, the sound engineering principles

(From "Notes on the History of Ancient Roads and Their Construction," by R.J. Forbes)

ROMAN ROADS in BRITAIN



Road through Medway Valley near Rochester



Fosse Way near Radstock

(From "Notes on the History of Ancient Roads and Their Construction." by R.J. Forbes)

Fig. 1

of proper drainage, adequate preparation of the subsoil, and general road planning as developed by the Romans have survived to this day.

Roads from Roman Times to the 17th Century

ENGLAND -- After the withdrawal of the Roman Army in A.D. 406, central government, and with it the need for military roads, collapsed. It is probable that maintenance of the Roman roads in certain areas of England was kept up for a long time, for several roads were still in good condition in the twelfth century. Other dirt roads were developed by people who preferred driving their animals on soft ground rather than on hard pavements, and many of these in time supplanted the Roman roads in popularity. As feudalism developed each little stronghold could render its position more secure by decreasing accessibility to it. Such an attitude could hardly be expected to result in the improvement of roads.

There were, however, certain elements of the population interested in maintaining passable roads, the merchants and the religious. Roads were indispensable to the success of fairs held during the Middle Ages, and it was at these fairs that most of the business of the country was conducted. The central authority of the Church required good communication between the various monasteries, and pilgrimages were encouraged. The decline in the fifteenth century of the monasteries and their dissolution in the sixteenth led to a serious deterioration of the roads, for the monks had long been taking alms for road

maintenance. In the falling off of population, brought the roads.

Sporadic attempts were made by the government throughout the Middle Ages to improve road conditions, but little real progress resulted. The first attempt from Parliament came in 1285 when owners of lands were enjoined to make the roads safer from ambush by cutting down trees and bushes a distance of two-hundred feet on either side of the road. In 1346 Edward III placed a toll on some of the roads out of London, and during the reign of Henry VIII (1509-47) certain laws were passed binding parishes to care for their roads. The first regular pavement was begun in London, according to statute, in 1532, cobblestone and pebbles being imported from the sea-shore for the purpose. Parliament had previously ordered the Strand paved in the fourteenth century and streets outside of London in the sixteenth.

While carts and wagons had long been known in England, luxury carriages, if indeed the term "luxury" can be employed, were unknown until the middle of the sixteenth century. Stow in his "Summary of the English Chronicles" tells us that in 1555 Walter Ripon made a carriage for the Duke of Rutland, and nine years later queen Elizabeth was presented a coach by one William Boonen, a Dutchman. By 1560 carriages were in general use among the wealthy classes. Although the introduction of the carriage brought no immediate improvement to roads, its subsequent effect on their development was far reaching.

FRANCE -- The story of the road in France as well as in the other more highly developed parts of Europe parallels that of England. The withdrawal of the Romans and the advent of the

Dark Ages, with the falling off of populations, brought the roads to a sorry state. A flicker of enlightenment and improvement came during the time of Charlemagne (771-814) as he sought to consolidate his empire, but the effort soon followed him to his grave.

Again we see disjointed efforts at improvement which had little effect on permanent development. In the reign of Philip Augustus the first pavement was laid in Paris (c 1184). Louis XII in 1508 appointed road inspectors, but the results obtained would indicate that most of these individuals were better politicians than engineers. In 1556 a stone road was built from Paris to Orleans, the entire width of the road being 54 feet, 15 feet of which were paved. A "Great Waywarden of France" was appointed by Henry IV in the latter part of the sixteenth century, but again we have little evidence that much was accomplished by the move. Sully initiated work on a national network of roads, paving with broken stone in 1597, but his successor, more interested in external affairs, soon dropped the project. So, by the beginning of the seventeenth century, France, along with the rest of Europe, found her roads in a much worse condition than they had been in centuries before under the Romans.

PERU -- During the Dark and Middle Ages in Europe a highly inter-developed civilization was flourishing in South America under the Incas of Peru. Archaeologists and historians have yet to tell the great story of these people but we already have substantial evidence of some of their engineering achievements. writing in the first half of the nineteenth century, W.H. Prescott

in his "History of the Conquest of Peru" (London, 1847) noted:
"The traveller still meets, especially in the central regions of the table land, with memorials of the past, remains of temples, palaces, fortresses, terraced mountains, great military roads, aqueducts and other public works, which, whatever degree of science they may display in their execution, astonish him by their number, the massive character of the materials, and the grandeur of the design. Among them, perhaps, the most remarkable are the great roads, the broken remains of which are still in sufficient preservation to attest their former magnificence."
Some writers have gone so far as to compare the Incan roads with those of the Romans; certainly the Peruvian roads were a wonder in their day.
There were many of these roads throughout the kingdom, but probably the greatest were the two roads which extended from Quito to Cuzco, the capital, and thence southward toward Chile. One of these roads passed along the lowlands on the border of the ocean, while the other more difficult route traversed some of the roughest, most mountainous country in the world. Prescott placed estimates as to the length of the latter road between 1500 and 2000 miles, for only scattered fragments remained in his time. The breadth of the road was approximately 20 feet, and stone pillars, in the manner of milestones, were placed along the route at intervals slightly exceeding a league. The road itself was made of heavy flags of freestone, covered over in some instances with a bituminous cement which time made harder than the stone. This knowledge was not communicated to the rest of the world, however, and the Incan influence never made itself felt in the subsequent

development of the road. Up until this time the road was called upon only twice a year, in spring and in autumn, to repair the roads. Roads of the 17th and 18th Centuries were applied to maintain the traffic during the long intervals between repairs.

FRANCE -- The renaissance in the art of road-building first appeared in France. A French lawyer, one N. Bergier, discovered the remains of some Roman roads in the vicinity of Rheims, and in 1622 published an account of them entitled, "Histoire des grands chemins de l'Empire romain." A modified version of the Roman road was adopted but did not appear to any great extent for some time. In 1661 Colbert, Louis XIV's far-seeing Minister of Finance, endeavored to bring about an enlightened policy regarding road planning, construction, and maintenance, but no material progress was made until 1700, except for the construction of a few roads near Paris. The first important article on the subject of road making came in 1693 when Hubert Gautier published his "Traite de la construction des chemins," and this together with the establishment of the Corps d'Ingénieurs des Ponts et Chaussées in 1716 gave added impetus to road construction of the period. In the modified Roman method, roads were generally laid to a width of 18 feet, with a depth of 18 inches at the crown sloping off to a depth of 12 inches at the sides, the subgrade being horizontal. The road was formed by laying flat stones in two or more layers at the bottom of the excavation, and this in turn was covered by two layers of smaller broken stones.

This method of construction was used until the efforts of the minister Turgot resulted in the abolition of compulsory road

labor (la corvée) in 1764. Up until this time the statute labor was called upon only twice a year, in spring and in autumn, to repair the roads; thus, large quantities of stone were applied to maintain the traffic during the long intervals between repairs. The abolishment of the "corvée" meant that a new method of constructing highways at a greatly reduced cost must be found. The problem was finally solved by Pierre M.J. Trésaguet (1716-1796), then chief engineer in the district of Limoges, France. He decreased the depth of the road to 10 inches, cambered the subgrade as well as the surface, laid his foundation stones on edge, and covered them with one layer of smaller hand-laid stones and a top layer of walnut-sized stones spread with a shovel. His method was generally adopted in France in 1775 and remained in effect until macadam construction superceded it officially in 1830, having been introduced in France about 1820. Trésaguet's system of constant maintenance made French roads the best of their day.

quats system of roads is called at the present day the "Trésaguet system".

ENGLAND -- With the increase of carriages came laws, not to improve the roads, but to restrict the vehicles. Thus, in 1622 James I decreed that all carriages could have only two wheels, and further restrictions were imposed in 1629 by Charles I. No improvements resulted until after the restoration of Charles II, when in 1661 the previous restrictions on carriages were modified. It was at this time that turnpike trusts came into existence, taking their name from the swinging toll gates usually made of sharpened poles. These were private corporations which were allowed to charge tolls in return for maintaining their particular stretches of road.

The first turnpike gate was erected on the Great North Road in 1663 to collect tolls for repairs in Hertfordshire, Cambridgeshire, and Huntingdon. So unpopular was the system, however, that no gate was erected between Glasgow and Grantham for a century. The trusts increased and multiplied nevertheless as evidenced by the fact that five hundred and thirty Acts of Parliament concerning turnpike legislation were passed in a period of seventy years (1700-1770). It was noted in Cresy's "Encyclopaedia of Civil Engineering" (1847) that over 1100 such trusts were in existence at the time, covering over 20,000 miles of roads. The rise of the railroads played a big part in their elimination, and the last trust at the western end of the old Holyhead road ceased to operate in 1895.

Although the first stagecoach between Edinburgh and Leith was run in 1610, and a fortnightly stagecoach service between London and Edinburgh was begun in 1658, there was still no adequate system of roads in Scotland at the beginning of the eighteenth century. The sharp need for roads was driven home when the rebellion of 1715 in the Highlands showed that regular troops could only accomplish a pacification mission with the mobility good roads would give them. Accordingly, General Wade built 250 miles of roads with his troops from 1726 to 1737, thus opening up the country to peaceful development as well. These roads were for the most part about 16 to 18 feet in width, and had a pitched foundation covered by small stones and gravel. Their value to the inhabitants concerned is reflected by the couplet commemorating the job:

"Had you seen these roads before they were made
You would lift up your hands and bless General Wade."

One might infer from the large number of turnpike trusts and ventures similar to General Wade's that English roads had improved considerably during the eighteenth century. That such was the case was not a view shared by Mr. Arthur Young who, in the second edition of "Six Months Tour in the North of England" (1771), wrote: - "To Wigan. Ditto. (Turnpike) I know not, in the whole range of language, terms sufficiently expressive to describe this infernal road. To look over a map, and perceive that it is a principal one, not only to some towns, but even whole counties, one would naturally conclude it to be at least decent; but let me most seriously caution all travellers, who may accidentally purpose to travel this terrible country, to avoid it as they would the devil; for a thousand to one but they break their necks or their limbs by overthrows or breakings down. They will here meet with rutts, which I actually measured four feet deep, and floating with mud only from a wet summer; what therefore must it be after a winter? The only mending it receives is the tumbling in some loose stones, which serve no other purpose but jolting a carriage in the most intolerable manner. These are not merely opinions, but facts, for I actually passed three carts broken down in these eighteen miles of execrable memory."

At about the same time that Arthur Young wrote, John Metcalf (1717-1810), known to some as "Blind Jack of Knaresborough," began a road-building-career which spread over a period of thirty years. Blinded as the result of an illness at six he developed a keen sense as to the fundamentals of road building such as firm

foundations and arched surfaces, and in his time built 180 miles of turnpike roads, having started from a humble 3-mile stretch on the Harrogate-Boroughbridge road in 1765. He was the first contractor to use any scientific principles at all on the turnpike roads, and is therefore remembered as the British forerunner of Telford.

Although records indicate that the British brought the UNITED STATES -- While inheriting many of the fine traditions from the mother countries of Europe, this blossoming country also inherited some of the poorer traditions, poor roads being among them. The new settlers had not seen good roads back home, and did not expect them in this wilderness, especially when the business of just making a living and fighting the Indians occupied most of their time. An attempt at paving was made at an early date in the settlements, the first known paving at Pemaquid, Maine, dating possibly to 1625. As a result of the complaining of housewives about the dust raised by brewery wagons, the street later known as Stone Street in New York was paved with small stones in 1656. By 1660 the main streets of New York were all paved with cobble stones, the gutters running down the center of the streets. Boston was also paving her streets at about the same time, records showing that such paving existed by 1663.

The first important road in the colonies, the old York road between New York and Boston, was laid down in 1711 mainly in the interests of commerce. Military roads then made their appearance. In forcing the French out of the Ohio Valley it was necessary to push military roads from Virginia across the Alleghany Mountains. George Washington was among the first when he laid out a road over

this route in 1754, and General Braddock in 1775, in an expedition against the French, used the same general route as laid out by Washington. However, little real progress was made in road making until the turnpike trusts appeared in the latter part of the eighteenth century, when a wave of enthusiasm swept the country for better communication between all parts of the Union.

Although records indicate that an earlier turnpike road in Virginia between Alexandria and the lower Shenandoah was started in 1785, the first important one was the Lancaster Turnpike (1792-94) connecting the metropolis, Philadelphia, and the largest inland city, Lancaster. This road, originally laid out by David Rittenhouse, was 62 miles long, 66 feet wide, and covered for a width of some 20 feet with 18 inches of pounded stone. Originally this stone was of all sizes and shapes, covered with earth, but, because of the unsatisfactory conditions resulting, the surface was later changed to macadam.¹¹ It appears that the right of eminent domain in an open and wholesale fashion was used for the first time in the United States in the laying out of this road. So ripe was the country for the turnpike method of construction, that a lottery had to be held to determine who the lucky subscribers to the venture would be.

While definitely not an eighteenth century road in any sense of the word, it might be well for the sake of continuity to mention briefly the Cumberland Road or "National Pike." Conceived in 1802 for the purpose of aiding westward expansion, it was to extend from Cumberland, Maryland, to a point in West Virginia, but the idea was expanded with the years until it almost reached the Mississippi near St. Louis. The first contracts were let

in 1811 and the project was carried on under Army engineers for the better part of forty years. Although constructed as a national project, sovereignty was gradually surrendered to the various states through which it passed, and they soon assessed tolls for its use. It ceased to be a through route for passengers and mail upon completion of the Baltimore and Ohio Railroad in 1852-53, and was not revived as a thoroughfare until the advent of the automobile.

RUSSIA -- Borrowing from western European ideas Russia began building roads during the eighteenth century. Peter the Great and his successors built the "Prospective" Road from Moscow to St. Petersburg, completing it in 1746 after a construction period of twenty-six years. It was later macadamized in the period from 1817 to 1834. Paul I had the first macadam highway in Russia built in 1797, the Tsarskoye Syelo-Gatchina.

PROGRESS SUMMARIZED -- It was during this period that the first rumblings of the modern concept of the road were heard. The French, fortified by their knowledge of Roman construction, were the first to point the way, and they were seconded by the English. The state of roads in all the rest of Europe, with the possible exception of Sweden, was deplorable, even by the English standards of Arthur Young's days. This was a period of great exploration and growth, and ideas quickly spread. An expanding interest in commerce and the re-kindled fires of nationalism brought to the people a growing interest in their roads, an interest which led to the development of the modern road in the nineteenth century.

THE 19th CENTURY - MODERN ROADMAKING APPEARS

EARLY IDEAS -- Although France had realized at an early date that true progress in road making could only be achieved by the application of engineering principles, such an idea did not penetrate to any extent any of the other countries, until England awakened in the early part of the nineteenth century. The attitude which had prevailed prior to 1800 was partially summed up by Sir Henry Parnell who, in the early part of the nineteenth century, stated that civil engineers "had been too commonly deemed by turnpike trustees as something rather to be avoided, than as useful and necessary to be called to their assistance." Then too, road making was regarded as something below the calling of an engineer; thus the engineer, Smeaton, caused a great deal of surprise when he built a road across the valley of the Trent between Markham and Newark in 1768. In general, maintenance of the roads was left to the unskilled and incompetent, as testified by the accepted method of repair known as "barreling the road." This method, described by C.W. Ward in the 3rd Report of the Parliamentary Committee of Turnpikes and Highways (1809), consisted of throwing dirt and refuse on the road until a semi-circular section was obtained, after which traffic was expected to consolidate the mass. Naturally vehicles would keep to the center of the road to avoid turning over, and soon the whole road would become rut-ridden. It remained for two Scotsmen, Telford and M^rAdam, to lead the way to progress in England--a progress which eventually was communicated to the rest of the world.

TELFORD -- Thomas Telford (1757-1834), originally a stone mason and later the most illustrious civil engineer of his day, began his first big road job in Scotland at the request of Parliament in 1802. The deterioration of General Wade's roads and the lack of communications in other sections of Scotland made new roads imperative to the well-being of the country. Attacking the job with enthusiasm, Telford built 920 miles of road with 1117 bridges under 120 contracts in eighteen years, with not a single suit resulting. He was, during the course of his lifetime, associated with many road projects, but his fame as a road-maker comes in a large part from his Holyhead Road, the mail road from Shrewsbury to Holyhead, completed in 1830.

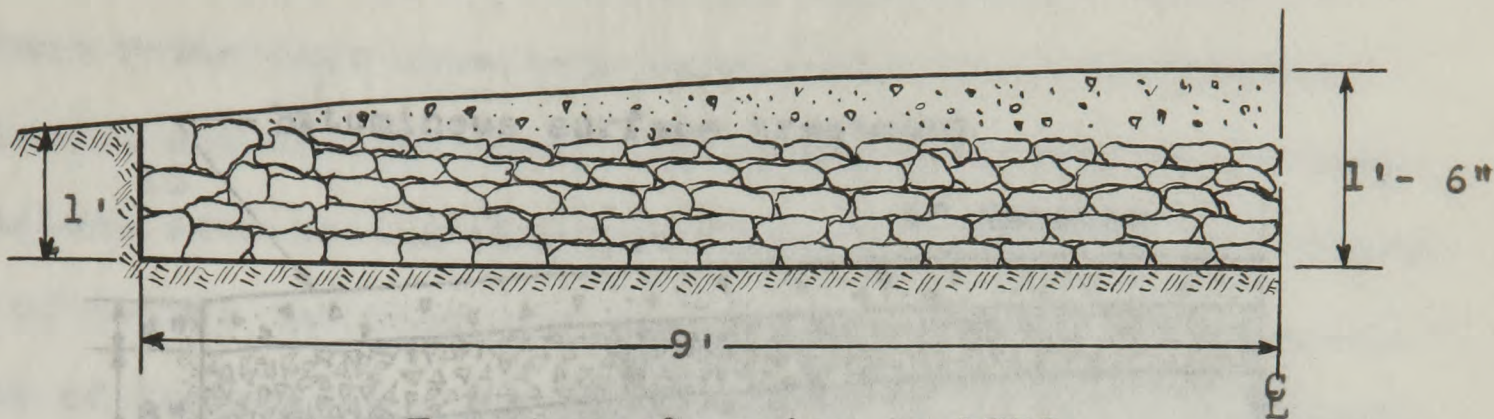
At the time, this road was the finest in the kingdom and exemplified what later came to be known as "Telford Construction." Essentially it was the same type of road as built by Trésaguet except for the fact that the subgrade was made horizontal, and cambering of the surface was achieved by using higher foundation stones (on edge) at the center of the road than at the sides. It might be well to note that what we today call "Telford Construction" has in fact a cambered subgrade, and is, therefore, in reality a Trésaguet type. Telford's contribution, however, was great, for he was the first engineer in England to lend his talents to modern organized road building on such an important scale.

M'ADAM -- Although John Loudon M'Adam (1756-1836) did not take the title offered him by the king for his services, nor consider

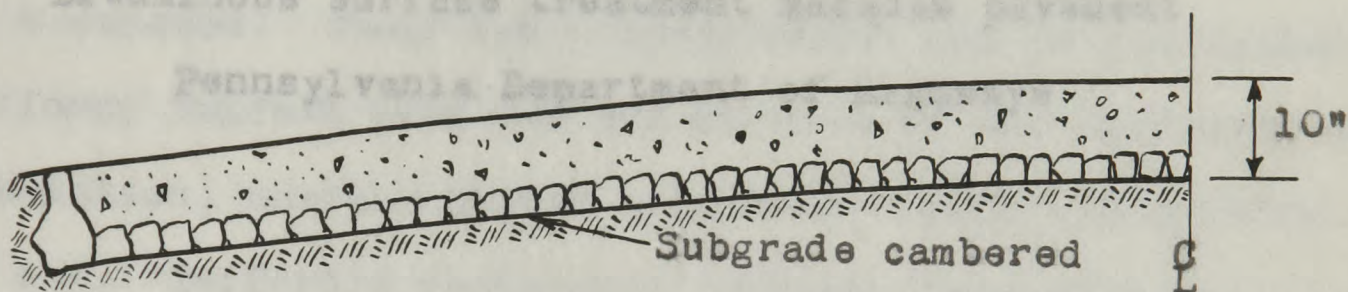
himself an engineer, nor invent the system which bears his name, nor even claim that he did, his contributions have justified the immortalization of his name in the term 'macadam' for broken stone when used as a road metal, and the oft-used verb, 'macadamize.' Upon his return in 1783 from a stay in America, he took up duties as a road trustee in Ayrshire and began his road-building practice which eventually led to his appointment as Surveyor of Roads, Bristol in 1815. Here he was better able to put into practice his theories of road building and repair, and quickly won the attention (and job of general surveyor) of several road trusts in England and Scotland. His later position as Surveyor-General to the Commissioners of Metropolitan Turnpike Roads enabled him to establish his system all over Britain. His methods and writings soon established for him a world-wide reputation, and his method of construction eventually spread to all countries.

His principle is described briefly by his statements, "that every road is to be made of broken stone, without mixture of earth, clay, chalk, or any other matter that will imbibe water and be affected by frost," and, "to put broken stone on a road which shall unite by its own angles so as to form a solid, hard surface." He built his roads on levelled and drained surfaces, varying the depth of the broken stone section according to conditions, rarely exceeding 10 inches. In his report to the House of Commons in 1811 M'Adam stated that, "every piece of stone put into a road, which exceeds an inch in any of its dimensions, is mischievous," but his specifications usually required a 6 ox. stone, no mention being made of its linear measurement.

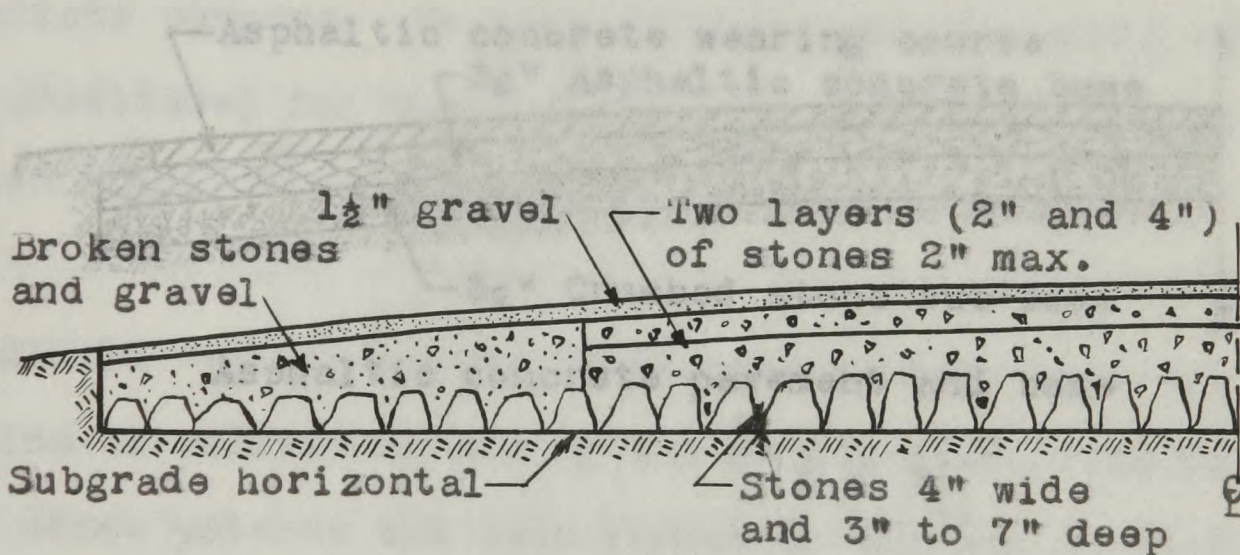
EARLY MODERN ROAD CROSS-SECTIONS



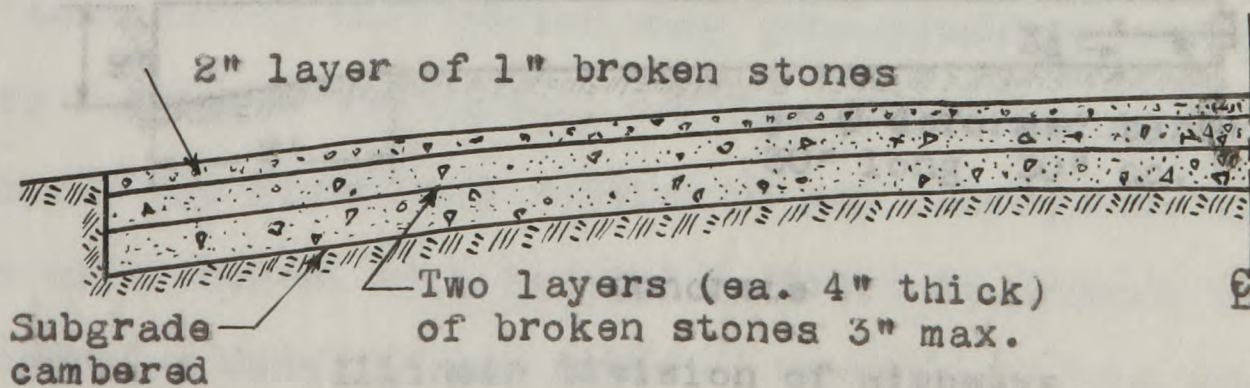
French roads prior to 1775



Tresaguet construction in France after 1775

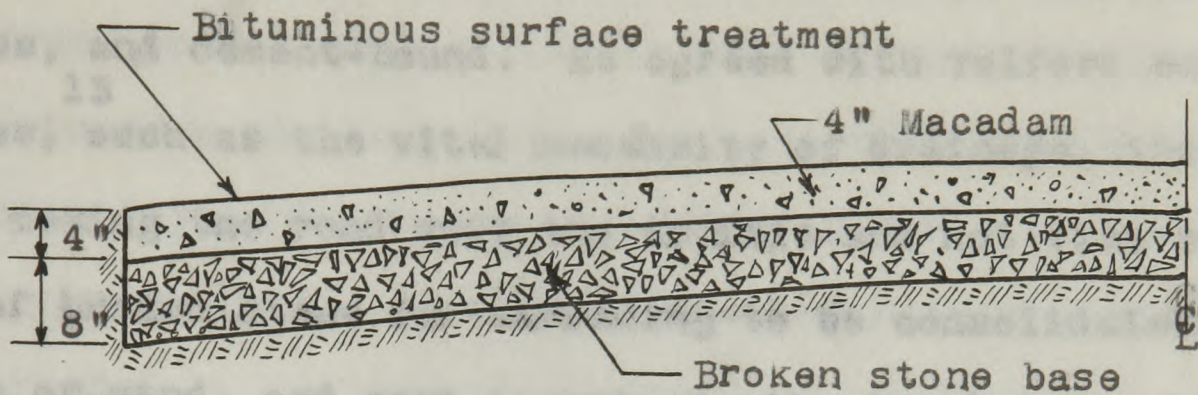


Telford construction, early 19th century



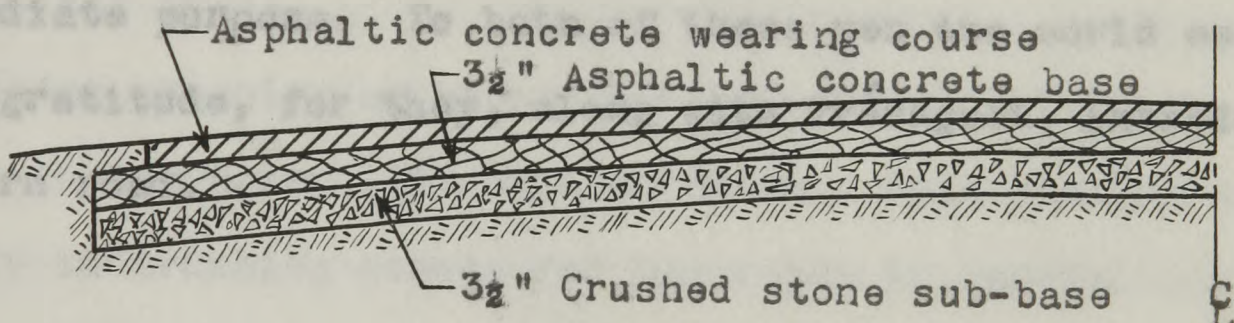
Macadam construction, early 19th century

MODERN ROAD CROSS-SECTIONS

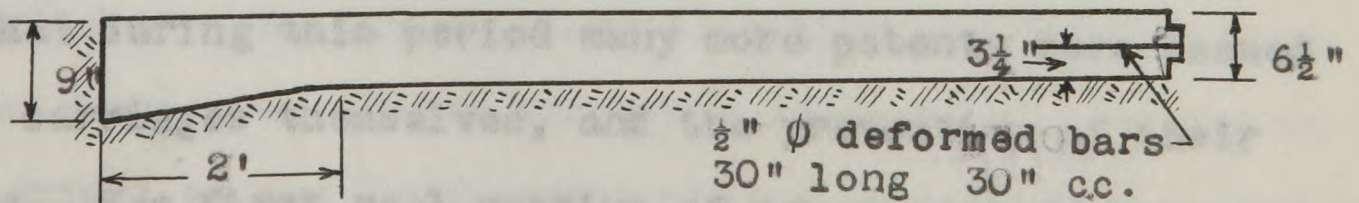


Bituminous surface treatment Macadam pavement

Pennsylvania Department of Highways



Asphaltic concrete pavement and base



Concrete

Illinois Division of Highways

M'Adam's conception of a road was what we would now call traffic-bound macadam, and since his time various types of "macadam" roads have come into existence: viz., waterbound, bituminous, and cement-bound. He agreed with Telford on many principles, such as the vital necessity of drainage, the importance of making the road suit the traffic and not vice versa, the use of broken stone for surfacing to be consolidated without earth or sand, and most important, the treatment of road making as a science. Their main disagreement was in the matter of foundations; Telford took the modern view of the necessity of a firm foundation, whereas M'Adam preferred a soft sub-stratum to a hard one. Telford's roads were probably over-designed, while M'Adam's roads were simpler, quicker, cheaper, and suited the immediate purpose. To both of these men the world owes a debt of gratitude, for they, along with Trésaguet, introduced the modern road.

ROAD MACHINERY -- The early nineteenth century also saw the application of rollers in making the modern road. The idea was not new, since patents had been issued in England in 1619 to John Shotbolte and in 1699 to Nathaniel Bard and Edward Heming for machinery to level the road. It is interesting to note, however, that during this period many more patents were issued devoted to carriages themselves, and the prevention of their overturning. The first real machine of any consequence was built and experimented with in 1787 by Louis de Cessart (1719-1806), Inspector Generale des Ponts et Chaussées. The machine was a 7000-pound (old French wt.) cast-iron horse roller, 8 feet

long and 3 feet in diameter. But the first practical use of rollers did not occur until after Waterloo when they were adopted in England, Germany (Hanover), and France. Philip H. Clay in England developed a horse roller in 1817 which could be loaded with weights from six to twenty tons, and Polonceau used the first wooden roller in France in 1829. As early as 1843 General Sir John Burgoyne wrote a paper on the importance of rolling new made roads.

To Louis Lemoine of Bordeaux goes the credit for the first practical steam roller, which he patented in 1859. He was followed shortly in 1863 by two Englishmen, W.F. Bathe of Birmingham and W. Clark, the chief engineer of Calcutta, India. A decade later Andrew Lindelaf of New York obtained the first patent in the United States.

Machine crushing of stone was introduced in 1858 by a manufacturer in New Haven, Eli Whitney Blake. This machine was used initially in crushing stones for the roads in Central Park of New York City. From that time forward the idea spread, until now machine crushing is almost universal. The practice of crushing stone by hand has not yet died entirely, however, for the author saw it being done along certain roads in Kire in 1948.

THE AUTOMOBILE -- As the nineteenth century was drawing to a close a new machine was being born--the automobile. It was to have more effect on the development of the road in fifty years than any other element had had in the preceding five thousand. Even at this relatively recent date it is difficult to determine just who deserves the credit for the invention of the motor car,

propelled by an internal combustion engine. Samuel Morely, an American, is reputed to have driven a boat with a combustion engine in 1826, and George Brayton is said to have produced such an engine to drive a tram-car at Providence, Rhode Island, in 1852, but these works had little bearing on the subsequent development of the automobile. Siegfried Marcus, an Austrian, is reputed to have designed, built, and run such a vehicle on the streets of Vienna, but the details of the machine's performance are vague.¹⁴ The first successful gasoline-driven motor car appears to have been that produced by the German Karl Benz in 1885. His pioneer car was soon followed by that of his fellow countryman, Gottlieb Daimler, in 1886. Though working independently these men were not alone in their pioneering efforts.

In 1895 George Selden, an American inventor, took out a patent for a motor car which he had held since 1879. He had realized that the world was not ready for his invention at that early date and so deliberately held up the patent until the opportunity for the greatest financial gain presented itself. The year he picked was wisely chosen; for it was in 1895 that the first great road race between Paris and Bordeaux was held. Won by M. Levassor in a Daimler type Panhard and Levassor car, the race demonstrated two things: (1) that long distance motoring was practical and (2) that the often-doubted gasoline motor was sound. From this time on, the success of the automobile was assured. Within a decade the influence of the automobile began to be felt in the field of road design.

The first attempt at a modern stone pavement was the laying of Mr. Walker of granite setts, 3 inches thick and 9 inches long,

BLOCK PAVEMENTS -- The development of the road from the time of Telford to the present is probably best followed by studying the evolution of pavements. The word "pavement" is derived from the Latin 'pavimentum' and means "a floor rammed or beaten down"; hence pavement has come to be defined as the artificial surface of an improved roadway formed of hard or durable material. As we have seen, the first type of paving in evidence aside from cobblestones in both ancient and modern times was the hand-set block type used by the Romans. Cordova, Spain, under the caliph Abdor-ranman II is said to have been paved in 850, and orders were given by Philip II to pave the streets of Paris in 1184. Several of the principal streets of London were paved for the first time by royal command in 1417, and Augsburg began paving its streets shortly following 1415. However, no large-scale paving appears to have been done until Paris, in 1609, placed the responsibility for paving and upkeep on the city. Paving was begun with large square stones (about 10 or 12 inches) laid directly on the ground, with a slope toward the center of the street where the gutter was formed. The gutters were moved to the side and sidewalks appeared about 1825. Street in St. Petersburg. The blocks were small and rough. Rough blocks of granite appeared as paving in the borough of Westminster about 1761 and Philadelphia began using granite blocks in 1839. Broad smooth granite blocks were laid for wheel tracks in Commercial Road London in 1825, but what was probably the first attempt at a modern stone pavement was the laying by Mr. Walker of granite setts, 3 inches thick and 9 inches deep,

with mortar joints on Blackfriars Bridge in 1840. Tar and gravel joints made their appearance in Manchester in the early 1860's. In present day practice, a concrete foundation is used in almost every case with stone block pavements, but there is no evidence that such a foundation was used much before 1870. A cubical block manufactured from granite known as Durax in the United States and England, and as Kleinflaster in Germany made its appearance in Europe in 1865 and in the United States in 1913. These stone-block pavements have been used to good advantage in heavily travelled streets in industrial areas, but have not, in general, been used in rural or residential areas of the United States because of the economic and esthetic superiority of other types of pavement. The same cannot be said for all countries, however, for many miles of stone-block pavements still serve in Belgium and in northern France and England.

Wood-block pavements, though now practically obsolete, were received most enthusiastically when they first made their appearance in the early nineteenth century. A case in point is London, where 1100 square yards of wood pavement in 1839 had increased to 60,000 yards in 1842. M. Gourief, a member of the Russian Academy of Sciences, led the way in 1820 when he paved Great Sea Street and Million Street in St. Petersburg. His blocks were small hexagons fastened laterally with wooden pegs and laid in a small bed of crushed stones and sand. The interstices were filled with fine sand, boiling pitch was poured over the surface, and sand was strewed above it. The next appearance of wooden blocks came in the United States in 1835-36, when some were laid experimentally in New York and Philadelphia. It remained for the English,

however, to exploit the idea and make it known to the world in general. Although David Stead, a merchant in Winchester Street, London, received the first patent and laid the first hexagonal blocks in 1838,¹⁵ the fact that John Finlayson in 1825 and James Heard in 1832 had written on the subject (based on the Russian success), lead to a great deal of confusion as to the patent rights. Thus, patents were issued to thirty-seven different individuals between 1838 and 1841, most of the differences being in the size or the shape of the blocks. The most successful of the "infringements" were the wedge-shaped blocks patented by Mr. R. Carey in 1839 and first laid in London in Mincing Lane in 1841. The first blocks placed in England were laid directly on the sub-soil, but a 3-inch foundation bed of concrete was soon adopted by Mr. Stead, and that principle has existed to this day. Treating the wood with creosote was a step which shortly followed, resulting in what essentially exists today. The first blocks were dipped and it was not until 1896 that the modern process of creosoting was adopted. Wood-block pavements first appeared in the United States in Boston, Philadelphia and New York about 1840. Many types of wood have been used for these blocks, but the greatest success has been found with Norway pine, hemlock, tamarack, southern pine, and black gum. When the major portion of traffic was horse-drawn, the wood pavement was very popular in the city, because of its durability when compared with macadam and its quietness and good traction qualities when compared with granite setts. However, the changes in the character of the traffic and the advances made by other pavement types made wood pavements obsolescent in less than a hundred years after their

inception. While we have seen that brick pavements were used in ancient times, their "modern" use was made by the Dutch as early as the thirteenth century. Japan and Italy were known to have had this type of pavement in the early nineteenth century, and probably before. There is some dispute as to where brick paving first appeared in the United States, but it is generally conceded that a citizen of Charleston, West Virginia, laid the first strip at his own expense and in the face of a great deal of ridicule in 1870. By 1873 the city realized the value of the experiment and continued the street at the public expense. Bloomington, Illinois, also pioneered in this field by laying a two-course brick pavement about 1875. During the evolution of the brick pavement, various types of bedding courses have been tried, the more successful ones being sand, bituminous mastic, granulated slag, Portland cement mortar, and tar pitch. Advantages and disadvantages similar to those of stone-block pavements have restricted the use of brick pavements mainly to heavy traffic areas in the cities of today.

A type of asphaltic block was first introduced in Paris in 1837 where an attempt was made to pave the entrance to the Place de la Concorde. It could hardly be called a success, however, for apparently the blocks contained too much mastic and too little stone. Evidently the forerunner of the modern asphalt block appeared in San Francisco in 1869, made of crushed stone and Trinidad asphalt. The methods of construction were very crude, and it was not until 1880 that a powerful compressing machine made improved blocks possible and successful. At first limestone was used

exclusively in the blocks, but traprock, because of its greater durability, was substituted in 1893 and has remained popular ever since. These blocks have been used extensively in the United States and South America, and to a lesser extent in Europe. The first patent on these blocks was probably that of the Frenchman, Léon Malo, who early in the second half of the nineteenth century laid blocks successfully in Paris and in several French provincial towns. A fuller discussion of asphalt comes in the following section, but it is interesting to note at this point that the asphalt block closely resembles in size and shape the earlier clay brick, which in turn has evolved from the stone block. Asphalt bricks now find their principle use in industrial floors, roads, and driveways, for pavements in large cities, for pier decks, and for bridge and viaduct roadways.

Various other types of block pavements have made an appearance, but their use has been far from universal. The high first cost involved in laying a block pavement, tends to limit the introduction of blocks made of materials costing more than types already in use. For example, although a few rubber-block pavements have been laid where elasticity, freedom from noise, and low weight were required (as on the Michigan Avenue Link Bridge, Chicago), their cost in large quantities has been prohibitive. Molded blocks of concrete have been tried, but their use is now restricted to marking traffic lanes, safety zones, and the like. Iron blocks were laid on Cortlandt Street, New York about 1865, only to be torn up shortly thereafter, and "Unter den Linden" in Berlin received an "iron paving" in 1877 which was taken up in 1890. Today we see iron paving in the form of a web-like

structure on bridges, but iron blocks have disappeared. Among other materials which have seen service at one time or another are coal-tar, shells, slag, glass, leather, and hay. If the present trend is any indication, however, these materials, in block form especially, will see little service in the road of the future.

ASPHALT -- Rock asphalt (usually consisting of limestone or sandstone impregnated with asphalt or maltha) has been known apparently for several thousand years, open Roman mines having been discovered in Switzerland. We first hear of it from a German named Jost who, in 1626, discovered that asphalt found in a garden in Bannes could be worked when warmed. A Greek physician and language teacher, Eirini d'Kyrinys, made the first important discovery at Val-de-Travers, Switzerland during his travels from 1710 to 1712. His primary interest in the asphalt was for its medicinal properties, on which he wrote an enthusiastic "Dissertation sur l'asphalte au cement naturel decouvert---etc." (Paris, 1721). With several associates he formed a company to develop the asphalt for use in tanks, sewers, and basins at Versailles and for caulking ships, but he later lost his concession owing to trickery in connection with the company. Although some work went on during the next hundred years, it was not until the exploitation of the Seyssel deposits in France that interest was rekindled in the Val-de-Travers mine. Obtaining a thirty-year concession in 1837, M. Antoine Brémond succeeded in producing a cement "exactly similar to that of Seyssel," and sold his holdings as a successful concern to Comte de Sassenay in 1838.

By discoveries of native and rock asphalt we find that its value to its finders lay in its

Dr. Eyrinis was also the discoverer of the German rock asphalt deposits at Limmer in 1730. They were not worked commercially until 1840, from which time they operated continuously until World War I. Another German deposit of historical interest is the Vorwörhle, discovered in 1601 by a woodsman and opened commercially in 1868. French deposits were also known from early days, especially in the Gard district where peasants used the asphalt to treat skin diseases of their animals. While no longer used in road-making, the Seyssel rock asphalt deposits in another section of France played a large part in the early development of the industry. These deposits first came to notice in 1797 when Sieur Secrétan obtained a concession to extract bitumen from the "green molasse." Another notable European source has been the Italian deposits at Ragusa, discovered in 1838, and first seriously worked in 1880.

The largest and most important sources of native asphalt are found in Venezuela and on the island of Trinidad. To Sir Walter Raleigh is given the credit for the Trinidad discovery in 1595, although his report did not mention his actually seeing the Lake. His main interest in it was its value for caulking ships, especially since its melting point compared very favorably with that of the wood pitch from Norway. His discovery was little noticed for over two hundred years until Dr. Nicholas Nugent, in a paper published in the "Transactions of the Geological Society," 1811, drew attention to the value of the Lake for caulking ships and criticized the British government for not exploiting the find.

Thus, in reviewing the early discoveries of native and rock asphalt we find that its value to its finders lay in its

medicinal and caulking properties and bore no relation to road making at all. Modest beginnings were made in 1827 when the Société Byquem began the exploitation of asphalt for terraces and paving, and the first big expansion came in 1838 when Paris adopted mastic for footpaths. The French engineer, De Courlaine, had before 1837 used asphalt rock, broken into fragments and heated, on short stretches of road between Bordeaux and Bayonne as a top dressing for ordinary macadam. M. Claridge obtained a patent in 1837 for using Seyssel asphalt for paving purposes in the Département de L'Ain. However, the first real asphalt pavement seems to have originated about 1849 with a M. Merian of Bâle, an engineer at the asphalt mine of Val-de-Travers. He noticed that the road between the mine and mastic factory seemed to be altering for the better, as pieces of rock asphalt in falling off the wagons were ground to powder by the wagon wheels. Accordingly he built an asphalt road from Travers to Pontarlier; he reduced the rock asphalt to powder by heating, spread it evenly, and then rolled it. Although he neglected the subsurface conditions, the road stood up very well for several years and furnished the inspiration for subsequent development.

Merian was followed by the engineer Léon Malo who, after several years of experimentation, was successful in paving with sheet asphalt the Rue Bergère in 1854 and the Rue St. Honoré in 1858. Napoleon III is said to have favored asphalt over stone block pavements because of the difficulty with which street barricades could be erected on the former. As in Paris, compressed Val-de-Travers powder was used to lay the first asphalt pavement in London on Threadneedle Street in 1869. From here

the method soon spread to other countries.

The use of the natural asphalt from Trinidad Lake for paving was begun earlier than that of the Val-de-Travers deposit, but not with as much success. Sir Ralph Woodward, Governor of Trinidad from 1813 to 1828, in a desire to keep down the weeds and grass in Brunswick Square, tried to use this asphalt in developing the road surfacing in the town of Port of Spain but found that the admixture of asphalt with the soil only "added to its fertility." Interest in the deposit lapsed until the results of a geological survey--carried out in 1855 by G.P. Wall and J.G. Sawkins, (published in 1858)--indicated that the material could be exploited successfully. As a result, the first real commercial venture was begun in 1864. Strangely enough, Trinidad asphalt when tried in London was a failure, though a success in the United States; and conversely, Seyssel rock asphalt, though well received in Europe, was unsuccessful when tried in New York in 1870.

Although a type of "asphaltum" was used for some sidewalks in Philadelphia before 1839, the general development of asphalt roads was confined to Europe where the asphalt mines had been discovered. A Belgian chemist, H.J. Smedt, was the pioneer in the United States who succeeded in imitating rock asphalt with Trinidad asphalt, so far as their natures permitted. He laid the first sheet asphalt paving in the United States in William Street, Newark, New Jersey, in 1870 or 1871. It consisted of a mixture of sand, limestone powder, and asphaltic cement, which apparently came from Richie County, West Virginia. His successful paving of Pennsylvania Avenue in Washington, D.C. in 1876

touched off a construction wave which soon made asphalt the most popular of paving materials. A poll taken in 1910 of four hundred and sixty American cities showed that sheet asphalt led all other pavements in square yardage, second place going to brick.

A natural result of the technological and chemical advancements in the petroleum industry--and the development of the motor car with its demand for better roads--was the production of asphalt from the fractional distillation of petroleum. So today we have various types of natural or manufactured asphalt pavements, such as asphalt macadam, sheet asphalt, and asphaltic concrete. In addition, of course, we still have the original rock asphalt type. The smooth riding qualities, cleanliness, and economy of construction and repair have won for this type of pavement the popularity it deserves and enjoys today.

TAR -- While the use of tar (produced as a distillate by the destructive distillation of organic material) as a surface dressing did not appear to any extent before 1900, it was well known long before that time. Like asphalt it was valued chiefly for its caulking properties. As early as 1661 Becher and Searle were granted an English patent for making pitch and tar from coal, and similar patents were issued at intervals. The greatest advance was that made by Accum, an English chemist, who was the first to distill coal tar in closed vessels in 1815. Tared macadam was used for footpaths laid in Gloucestershire between 1832 and 1838, and the first English patent dealing with the application of tar to roads was issued to Cassell in 1834. Another early patent was issued in 1838 to Alexandre Happey, who

followed up with a small amount of actual construction. In 1850 Mr. H.V. McKie placed a tar-macadam paving on the railroad platforms in the vicinity of Lancaster. In France, Francau of Auch in 1871 layed cold tar and then set fire to it to harden the surface. The most extensive experiment up to the beginning of the twentieth century was that of Girardeau, who in 1896 applied hot tar to the road surface, having previously observed the beneficial effects of the hot sun on cold tar application.

One point concerning tar worth noting is the fact that from about 1860 organic chemistry began demanding increasing quantities of coal tar distillates. As a result, pitch became an unwanted, and therefore cheap, by-product. The supply of pitch was further increased when the demand for benzol for motor fuel was raised.

The turn of the century saw the entrance of the motor car, and with it came the greatest menace of the day--dust. Practically all roads outside and many roads inside of cities were water-bound macadam, obviously not suitable for the new high speed, rubber-tired automobiles. The first systematic experiments to combat the dust menace were begun by Dr. Guglielminetti in 1901 at Monte Carlo, Geneva, and Nice, where he had coal tar brushed into the surface of the road. As a result of his experiments, the Department of Engineers of France were induced to try their own experiments at Champigny, and in 1903 they formulated their basic principles on superficial tarring which have lasted to this day.

The initial fight to keep down the dust in the United States was begun by using light oils, the first use of oil being made in 1894 at Santa Barbara, California. Heavier oils were

introduced in the course of time, and surface tarring came into use in 1906. The original idea of dust prevention was soon joined by that of road preservation, and that concept has existed to the present. Thousands of miles of tar roads in countries all over the globe today testify as to the contribution made by the road pioneers of France, the United States, and Great Britain.

CONCRETE -- The use of concrete for road foundations is not new, for the Romans used a type of concrete in their construction. The extensive use of concrete as a pavement, however, is a twentieth century innovation, one that even yet has not captivated the fancy of all the world. Early uses of "concrete" were confined to structures, and it was not until the early 1880's that it came into use as a bedding course for wood-block pavements. Its value as a bedding course for all other types of pavement soon came to be recognized, and that use has come down to the present.

History records the first experimental concrete paving as a piece 150 feet in length laid at Inverness, Scotland in 1865. In 1886 Joseph Mitchell, an Englishman, laid a concrete-block pavement on the George IV Bridge at Edinburgh. His blocks--2½ to 3 inches wide and 5 inches deep--were laid on a Portland cement concrete bed, the joints being filled with cement grout. Grenoble, France, received a concrete pavement in 1876, and Bellefontaine, Ohio, became the first city in the United States in 1893 to be so paved. Little progress was made, however, until the automobile became an important unit of transportation.

Being the home of the automobile industry, Wayne County,

Michigan, in 1909 commenced the establishment of an extensive system of concrete roads which spread rapidly to rural and metropolitan communities alike. Thus the United States took an early lead in concrete road investigation and construction, a lead somewhat reluctantly followed by other countries. P.J. Larranaga, writing in Paris in 1926 expressed the general tenor of that reluctance when he stated, "If considered in connection with country roads, for about three to four years a cement-concrete unsurfaced paving can be considered a not unattractive type of wearing surface, by those who have never seen anything but a potholed old macadam road. After that time the probabilities are that the concrete paving will be hiding its shame under an asphalt pavement." And, as another example, the British Isles had in 1935 only 3000 miles of concrete road.

The Germans under Hitler, however, preparing for world conquest, recognized the need for broad, heavy-duty highways, and traced and re-traced Germany with their famous autobahns in the 1930's. The Italians under Mussolini were also actively engaged at the same time in building up their road system, much of it of concrete construction.

Much of the early work was, of course, done by trial and error and results were not always of the best. A large amount of progress was made in the United States in the early 1920's on the test roads in Illinois (the Bates Road), Pittsburg, and Arlington. From these tests were derived certain principles of design, especially in reinforced concrete, which resulted in a greatly expanded volume of this type of construction. The separate base and wearing courses were combined to form a monolithic

structure, improvements were made in joint construction, thickened edges appeared, and reinforcing steel was introduced in a more scientific manner. To Clifford Older, an engineer in the Department of Public Works in Illinois, is given the credit for probably being the first engineer to design pavements on the basis of their analysis as a structure provided to withstand certain loads. Two other Americans, Professor H.M. Westergaard and A.T. Goldbeck, also deserve mention for their contribution to design principles.

The two World Wars emphasized the need for sturdy highways to take ever-increasing loads, and the new concrete roads were called upon to do the task. These roads of 6 to 8 inches in thickness were a far cry from their Roman predecessors with a thickness of 3 or 4 feet. The success of the modern concrete road has been, of course, attributable to many factors, some of the more important being: (1) the improved methods of producing mineral aggregates, (2) the studies in the expansion and contraction of concrete, (3) the investigations of structural action of concrete, (4) the improved quality of Portland cement, and (5) the advances made in the manufacture of machinery and tools for construction. It is not the perfect pavement by any means, but it is improving and gives every indication of continuing its increase in popularity.

AIRPORTS -- The automobile has not been alone in providing a motivating force for pavement development in the twentieth century; the airplane, too, has played an increasingly significant role in this field. Keeping pace with the evolution of larger and larger planes has been the increased attention devoted to

runway design and airport layout in general. Officially, we might say that the "Air Age" began on December 17, 1903, the date of the first flight of a power-driven heavier-than-air machine. On that historic day at Kitty Hawk, North Carolina, Orville Wright flew about 120 feet in an airplane he had designed and built in cooperation with his brother, Wilbur. Later on in the same day Wilbur Wright flew the plane 852 feet in 59 seconds. During the years 1904 and 1905 the Wright brothers perfected the details of their invention at the world's first airplane landing field, an 80-acre cow pasture 8 miles northeast of the center of Dayton, Ohio. In the early days of this airfield, take-offs were accomplished by means of a catapult arrangement, and landings were simply made on the grassy field.

The early increases in plane weights soon made some type of paving on the runways essential, so it was only natural that engineers should turn to the paving they already knew something about--the paving used for automotive transport. Thus, during its infancy, airfield construction became closely allied to road construction both in materials used and techniques employed.

World War II brought a great impetus to airfield construction, especially in the temporary or emergency category. Surfacing materials used during the conflict could be divided into three broad classifications:

- (1) Natural Materials - coral, gravel, volcanic ash, and selected soils.
- (2) Processed Materials - crushed gravel, crushed rock, etc.,
- (3) Artificial Materials - asphalt impregnated jute, bitumen, portland cement, and steel landing mat.

In the majority of cases emphasis was placed on the flexible type of runway where speed of construction was essential, but rigid ways were built where permanence was desired and where time permitted.

It is now clear that building an airdrome and building a road are not essentially the same operation any more. Airplane wheel and vibratory loads have increased way beyond the limits of any automotive (or even tank) loads to which regular roads are subjected. As a consequence, new design criteria are being established which are taking airport construction further away from the parent road construction. As yet, airport design is probably too new to be properly assessed in an historical sense, but there is every indication that its importance in civil and military life will continue to increase with much the same zest which has marked its rise in the first half of the twentieth century.

Summary of the Development of the Road

While prehistoric sources and ancient history are full of accounts of hunting trails, land trade routes, and paved cities of other civilizations, the first great road builders were the Romans. "All Roads lead to Rome" was no idle boast; it was a policy of empire. The tramp of the legion feet in far-flung corners of the world, where peace and order were maintained, was made possible only through the existence of the great Roman highways. Although built primarily for administration by a strong central government, their use for commerce and social

intercourse enriched every area in which they were laid. The fall of the Empire in the fifth century marked a decline in the development of the road which lasted until the eighteenth century.

There were a few bright spots on the way, of course. The Arab world produced some fine roads during the eighth and ninth centuries, but they had little effect on subsequent development. Charlemagne at the same time briefly revived the roads, for the same purposes which had inspired the Romans to do their original building. By and large, however, the breakdown of strong central governments and the advent of feudalism sounded the death knell of roads.

The Renaissance, with its increased interest in learning and in trade, did not immediately stimulate road building as might be supposed. It was not until France began imitating some of her well-preserved Roman roads in the seventeenth century, that much attention was given to the matter. Again, the hand of government was noticeably present in the effort. France still lead the world in the eighteenth century when Trésaguet, forced by economic necessity, developed the forerunner of the modern road. Under Napoleon, France continued her leadership in the early nineteenth century, for roads were vital to his scheme of conquest and administration. Alpine roads such as the Simplon carriage road built in five years by Cessart, and the Mont Cenis Pass built in seven years, give evidence of the ability of French engineers under Napoleon.

The Industrial Revolution in England during the early part of the nineteenth century emphasised the need for good roads to handle raw materials and manufactured goods readily. This

gave rise to the building by both the government and private interests, and gave men like Telford and M'Adam the opportunity of exercising their talents in this field. The English example was soon picked up by France, and then gradually spread to the rest of the world. Although city pavements continued to develop, roads outside of cities suffered a regression, which commenced in the second quarter of the nineteenth century and lasted to the early part of the twentieth. This was the Railroad Age, an age in which some enthusiastic railroad supporters predicted that carriages would disappear and roads outside of cities would become over-run with grass.

However, the twentieth century ushered in the automobile, and with it the demand for new pavements, especially on rural roads. The pavement in the city had developed rather logically from cobblestones furnished by nature, to quarried stone shaped by man to give a more even surface. Manufactured brick was the next step, followed by the use of asphalt, in block form, of course, which made a quieter and smoother pavement. To make the surface carpet-like was then accomplished by the use of sheet asphalt. The extensive use of concrete on highways was introduced by the United States to accommodate its ever increasing load of gasoline vehicles and to span its large distances.

Not only have the needs to be satisfied been important, but the availability of materials has played a significant role in the development of the road. Traditionally, stone and wood have been available for use from earliest times, but tar did not become available as a plentiful and cheap commodity until produced by the organic chemistry industry in the latter half of the

nineteenth century. In like manner, asphalt is largely a product of the latter nineteenth century when advances in rail and steamship services made possible its transportation at a reasonable cost. The development of concrete and steel--discussed at length in the chapter on materials--also belongs to the same era. Thus the automobile and the economical production of suitable road building materials joined together in the early twentieth century to give a new birth to road building.

Following the advent of the automobile, travel on the roads for pleasure created the initial demand for road development, but this demand was soon supplemented by that of commercial interests, and, to a certain extent, by that of military interests. The meeting of the First International Road Congress at Paris in 1908, followed by periodic meetings of the body, and the formation of various road societies throughout the world is indicative of the universal interest and concern in roads today. Such interest is bound to result in their improvement, and thus add to the comfort and enjoyment of the whole of society.

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Chapter IV

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BRIDGES

ably improving the suspension bridge by twisting vines and
 Development from Prehistoric Times to the 18th Century
 in the tropics as today. In time, four different kinds of
 MAN FOLLOWS NATURE'S LEAD -- The seeds of an idea on bridge-
 building were planted very early in the mind of man by the fun-
 damental types of bridges produced by nature. There was, for
 instance, the beam type exemplified by the fallen log across a
 stream. The suspension type was represented by tangled vines
 growing from one tree to another, while natural arches of cor-
 beled rock such as the Rainbow Arch in Utah, USA, provided yet
 another example. It is possible that the first builder of
 bridges was the Neolithic (New Stone Age) Man, who appeared in
 Europe about 15000 BC and who is known to have had tools such
 as a stone axe. With such a tool he could fell trees, place
 several side by side, and thus imitate and improve upon the ex-
 ample given him by nature. The next logical step was to im-
 itate the beam action of the logs with stone slabs and piers
 which would give greater stability as well as greater perman-
 1
 ence. Smiles noted the presence of a "Cyclopean" beam type
 bridge (later inhabitants attributed the work to giants) over
 the East Dart in England. Three piers of granite blocks carry-
 ing granite slabs, 6 by 15 feet, indicate that the
 structure might date from Stonehenge times, over three thou-
 sand years ago. However, the bridge commonly considered the
 oldest existing in the world is the Caravan Bridge, a
 foot stone slab type, over the River Meles in Smyrna, Asia
 Minor, reputed in legend to have been used by Homer.
 2

During prehistoric times man in warmer climates was probably improving the suspension bridge by twisting vines and creepers into ropes in much the same way that primitive peoples in the tropics do today. In time, four different kinds of suspension bridges evolved, the simplest type being the basket on a cable. In China it was known as the Liu Soh, or Lew Saw, literally "slip rope", the cable being of bamboo. Similarly the "tarabita" in Peru, described in 1748 by Admiral Don Antonio de Ulloa, consisted mainly of a cable, 6 to 8 inches in diameter, made of ox-hide thongs or bejuco. In China, central Africa, northern India, and South America we find early evidences of a hammock type of suspension bridge, wherein four cables were united with a web, providing a walk-way and enclosed sides. A roadway on the cables was another early type, one example being that of a bridge over the Apurimac River in Peru having a span of 148 feet at a height of 118 feet. The fourth type apparently originated with a primitive group in the Himalaya and is the one with which moderns are so familiar--the suspended roadway.

THE ARCH -- Although he had certain examples in nature, early man found it difficult to utilize the arch in his bridge-building, and it took him many centuries to bring it to a fully developed form. Naturally the corbeled arch, one built up of super-imposed cantilevers with a simple slab span enclosure, was the first to make an appearance, though not in the construction of bridges to any extent. The Sumerians, using brick for the most part, used the corbeled arch extensively,

but evidences of a true (voussoir) arch have been found in Mesopotamia dating to 4000 BC.⁵ While the corbeled arch was used by the Egyptians in the Pyramids at Gizeh almost five thousand years ago and the true arch was known by the 3rd Dynasty (2980-2475 BC), Egyptian arch construction was used more in a decorative than structural sense. Due to their imperfect understanding of its action and their inability to use it properly, the Egyptians are credited with the saying "The arch never sleeps." The first recorded postern bridge is credited to the

Archeologists have found numerous examples of the use of the corbeled arch by the Assyrians, Babylonians, and Chaldeans, but as in the case with their predecessors, we have no information on their bridge-building exploits, if any. A legendary story tells of a single brick arch bridge 660 feet long and 30 feet wide erected in Babylon during Nimrod's time (c 2200 BC).⁶ It is quite probable that this story had its origin in Herodotus' description of a later bridge built under Queen Nitocris⁷ spanning the Euphrates at Babylon, a timber-covered bridge made of cedar, cypress and palm, and supported by a hundred stone piers. Examples of the use of the semi-circular arch among early peoples have been found in Asia Minor, among the ruins of the Phrygian cities, and in Acarnania, the most western province of ancient Greece. Two other ancient examples of a true arch have been discovered near the Nile, one in a tomb at Thebes (1500 BC) and the other, which may possibly ante-date the first, in Ethiopia.⁸ However, it remained for the Etruscans, a race of Asiatic origin who entered Italy about 1300 BC, to develop fully and make extensive use of the true arch.

PRE-ROMAN CONSTRUCTION -- Just as our knowledge of arched bridges prior to Roman times is very meager, so too is our knowledge of other bridge types. We know from archeology that the pre-historic lake dwellers in Switzerland built crude wooden trestles on piles, and that the early Greek tribes ("Pelasgi") from Syria and Asia Minor built extensively in "Cyclopean" masonry. History, however, tells us little until the time of the Persians when bridges became an important adjunct to world conquest. The first recorded pontoon bridge is credited to the engineers of Cyrus the Great, who ruled Persia in the latter part of the sixth century BC. Cambyses, the son of Cyrus, extended the Persian conquests over most of Egypt, and then he in turn was succeeded by Darius Hystaspis (521-486 BC.) who greatly enlarged and consolidated his empire. Part of his scheme of consolidation included annexing a portion of Greece. His invasion of Europe was accomplished by sending an army--600,000 soldiers according to one version--across a pontoon bridge built by Mandrocoles of Samos and laid over the Bosphorus at a point where the straits were 3000 feet wide. A few years later the famous bridge of boats over the Hellespont at Abydos was built by the scientist Harpales to enable Xerxes to march into Greece as his father, Darius, had done before him. This expedition was also doomed to failure, however, and the Persians were defeated at Thermopylae (480 BC), never again to challenge seriously the rising supremacy of the Greeks. The art of building bridges, military or otherwise, concerned the Greeks very little, so it fell to the lot of the Romans to become the first great bridge-builders of antiquity.

THE ROMANS -- The first recorded bridge over the Tiber was the famed Pons Sublicius (Bridge of Piles), so bravely defended by Horatius Cocles against the Etruscans and Lars Porsena of Clusium, in the sixth century BC. Plutarch informs us that this noted wooden bridge was built (c 621 BC) under Consul Ancus Marcius (640-616 BC), and that its custody and maintenance were attached to the priesthood. So great a part did bridges play in subsequent Roman life that in time the head of the state adopted the title Pontifex Maximus (Chief Bridge-builder), a title which was later adopted by the Popes, and held by them to this day. The Pons Sublicius was originally destroyed about 500 BC, but was rebuilt several times until the last ruins were removed in 1877.

The Romans built many other timber bridges, the best known probably being Caesar's pile bridge across the Rhine (55 BC) erected for use in the Gallic Wars. Although Caesar left a description of the bridge, his account does not tell us definitely how it was built, nor even how long it was, but we do know that it was somewhere between 1300 and 1800 feet in length, in spans of 20 to 25 feet. A second famous timber arch bridge between 3000 and 4000 feet in length was that thrown over the Danube below the Rapids of the Iron Gate by Apollodorus of Damascus in Trajan's reign (AD 104). Another interesting bridge of classical times was the 3½-mile Bridge of Ships across the Bays of Baiæ and Puteoli, built to satisfy the whim of the half-mad emperor, Caius Caesar Caligula. This bridge held the distinction of being the longest non-military bridge in the world until 1903 when the Southern Pacific Company

built a 20-mile trestle, the Lucin-Ogden Cutoff, across Great Salt Lake. The only longer bridge during the period between these two was the one built in 1566 by the Turk, Suleiman the Magnificent--a 5-mile pontoon bridge across the Drave at Essek. However, despite the fact that probably most of the Roman bridge-building was done with timber, we have little evidence as to how it was accomplished, whereas we are deeply indebted to the heritage left us in masonry construction, examples of which are still available today.

As we noted earlier, it was the Etruscans who perfected the arch, but it remained for the Romans to utilize it on a large scale in the making of bridges. An early example was the Pons Solarius over the Tevere erected about 600 BC. under Tarquin, who was himself an Etruscan. The great bridge-building period started at a later date, however, about 300 BC, and lasted until about AD. 200, a period approximately identical with that of great road building. At least eight stone bridges were constructed across the Tiber during Roman time, and six are still in evidence. These six, in order of vintage, with original names in parenthesis are the Ponte Rotto (Pons Aemilius) (178 BC), Ponte Molle (Pons Milvius) (109 BC), Ponte dei Quattro Capi (Pons Fabricius) (62 BC), Ponte dei S. Bartolomeo (Pons Cestius) (46 BC), Ponte S. Angelo (Pons Aelius) (AD. 134), and Ponte Sisto (Pons Aurelius) (AD. 260). The Romans left other examples of their work outside of Rome as well, one of the most noteworthy being the Ponte di Augusto at Rimini, probably erected during the reign of Augustus (27 BC - AD. 14). This structure, whose piers are not at right angles to the bridge axis, is considered

by many the most beautiful of all existing Roman bridges.

While each of these bridges and others not mentioned have their own individual characteristics including long and interesting histories, it is sufficient for our purpose to note the similarities typical of Roman construction. The semi-circular arch invariably was employed whenever the Romans worked with stone, brickwork, or bricks over concrete. When working with stone they built up their arch rings with relatively soft limestones, such as peperino and tufa, and faced them over with blocks of hard travertine, anchoring these blocks to the interior by means of iron cramps. It was also customary for them to build an odd number of arches which gradually increased in span toward the center. The arch spans varied in size from 25 to 80 feet while pier widths were usually about one-third of the span. The arches of the aqueducts, on the other hand, generally had a span of about 18 to 20 feet, although spans as great as 120 feet were employed. The usual bridge widths, narrow by modern standards, seldom exceeded 30 feet. An outstanding feature of construction was the rather common practice of laying cut stone voussoirs without mortar, despite the fact that the Romans had developed a cement which was not equalled for centuries after the passing of their empire. Where time and money were no object, slave labor being in vogue, such precision stone cutting could be used extensively. They used little economy in constructing their sub-aqueous foundations, which were not constructed with the same skill as were the super-structures. In general, although wood piling was often used, boulders and rocks were dropped in a river bed until sufficient bearing was obtained,

and then construction of the pier was begun, a step-backed or battered pier foundation resulting. A final feature worthy of note is the fact that ornate decoration of a city bridge was considered most worthy and, in fact, necessary.

Although they will be taken up in a later chapter, the aqueducts of the Romans quite properly deserve mention in this section on bridges. Most eminent of all was the Pont du Gard in southern France. According to M. Menard, historian of Nîmes, it was the work of Agrippa, son-in-law of Augustus, who ordered the work to be done about 19 BC. This magnificent edifice-- which still stands in three tiers, the first consisting of six arches, the second of eleven, and the third of thirty-five-- towers to a height of about 160 feet and extends along its top for a distance of 885 feet. Its largest arch, though not at the center of the structure, does span the central portion of the river with an opening of 80 feet 5 inches. But let us turn from such a prosaic description to that of the gifted Charles Kingsley who in 1864 wrote to his wife: "---, we turned the corner of the limestone glen, and over the deep blue rock-pool, saw THAT THING hanging between earth and heaven, the blue sky and green woods showing through its bright yellow arches, and all to carry a cubic yard of water to Nismes, twenty miles off--- Then I felt the brute greatness of the Roman people; and an awe fell upon me---"

The Segovian aqueduct in Spain is another notable example, utilitarian in purpose, but beautiful in its simplicity and magnitude. It towers over one hundred feet above the small houses in the valley, its two-story arches carrying a cement conduit

2700 feet long. As in most Roman construction of this type its large blocks of stone were laid up in regular courses without any mortar. Still another example of two-story arch construction in Spain is the aqueduct at Tarragona.

Before leaving the Roman grandeur in Spain we must pause to mention two fine bridges which still exist. The first, located at Martorell in the province of Barcelona, is probably the oldest existing of the Roman bridges, dating from about 219 B.C. It has been thoroughly remodeled twice since Roman days, once by the Moors in the Middle Ages and again by Charles III of Spain in 1766. Its crowning feature is its central arch opening of 121 feet. And finally we note the Puente Trajan over the "melancholy Tagus" at Alcántara (from Al Kántaran-- Moorish for "The Bridge"), a favorite of many painters and writers. Erected in about A.D. 98 it has well withstood the ravages of time and still bears the inscription of its builder, Caius Julius Lacer--an inscription which characterizes the genius and determination of the Roman engineers: "Pontem Perpetui Mansurum in Saecula" (I have left a bridge that shall remain for eternity).

THE CHINESE -- While we know that a high state of civilization existed in China and in other parts of Asia before as well as after Roman times, our knowledge of that culture is too meagre to permit us to trace Asiatic influence on the progress of bridge-building in the western world and vice versa. All that we can do is to make a few comments on progress in China itself. According to legend the first great period of building came

sometime around 2300 B.C. under the Emperor Yao, when timber and pontoon bridges were introduced. Dr. H.G. Creel in "The Birth of China" (London 1936) asserts, however, that the earliest civilization known, historically and archaeologically, which can be called "Chinese" in a cultural sense is that of the Shang people living at Anyang in the fourteenth century B.C. Discoveries to date have revealed nothing as to their ability in the field of bridge construction. Later, after the time of Confucius (551-479 B.C.), the art of stone cutting had developed to the point where stone bridges became feasible, and by the time of the Han Dynasty (206 B.C. - A.D. 220) stone cantilever bridges had come into vogue. These cantilever types, still being erected today, were used for spans up to 100 feet or more, while suspension bridges were used for greater lengths up to 300 feet.

Various holy men of China brought back accounts of their pilgrimages to India in which they described certain construction types later adopted by the Chinese themselves. The monk Fa Hsien wrote of suspension bridges in A.D. 399, and in A.D. 630 Huang-Tsang described the use of iron chains in suspension bridge building in the Indus Valley. Another traveler of note, this time a visitor to China, was Marco Polo who recorded some of the progress which had been made during the Sun Dynasty (A.D. 960-1280). He made particular note of a stone bridge at Pulisangan, 300 "paces" long and 8 "paces" wide upon which ten men could ride abreast on horseback. This, however, is a digression, and we must return to the main thread of our story.

THE BROTHERS OF THE BRIDGE -- There was, generally speaking,

little activity in bridge-building in Europe after the downfall of Rome until the tenth century. The Moors during the interim were responsible for some progress, an example being that of the Alcántara at Toledo, Spain. An early Roman bridge at the spot was repaired in 687 by the Visigoths, but it disappeared in 871, only to rise at a later date under Halaf Alameri.¹² After subsequent destruction and restorations the bridge was finally restored in 1380 by Archbishop Pedro Tenorio. When building began again, it was largely in timber, the result being haphazard arrangements reminiscent of far earlier times. It is known that the Saxons built timber bridges over the Thames, one at the site of London Bridge existing in 994 according to an early account of William of Malmesbury.¹³ Furthermore the triangular stone bridge of Croyland near Peterborough, England, was mentioned in a charter as early as 943,¹⁴ but the precise date of its erection is unknown.

The Crusades of the eleventh and twelfth centuries had stimulated the minds of men, so that travel was resumed once more and an increased interest in improving his environment was developed by the Western European. According to Hubert Gautier, the author of the earliest work on bridges known (1728), travel conditions toward the end of the twelfth century had become so bad, however, that groups of pious monks banded together with the major object of offering travellers hospitality and getting them safely over dangerous rivers. With remains of Roman bridges as their guides, these monks set out to bridge many rivers in a permanent fashion becoming engineers, masons, carpenters, and laborers and then passing

these skills on to the laity. It appears that the *Pratres Pontifices* began with the Altopascio Order near Lucca, Italy, and spread to the Benedictines in France. Still later the movement took hold in England where the Benedictine monks became the acknowledged leaders in the thirteenth century. In 1189 Pope Clement III officially recognized the Brothers and they continued their bridge-building activities until some time in the fourteenth century when they were superseded by lay interests. At this time they confined their activities to the care of pilgrims, and were finally suppressed in 1459 by Pope Pius II.

The earliest leader of the Brothers of whom we have knowledge was Johannes Benedictus, later known as St. Bénézet, the builder of the fixed stone arch bridge over the Rhone at Avignon. When originally built in the decade commencing about 1177, this splendid example of the medieval bridge contained more than twenty elliptical arches, four of which still stand. An even earlier stone arch was built in 1146 across the Danube at Regensburg, Bavaria, but the names of its pious builders have been lost in the course of history. The most famous of all these medieval bridges was, of course, London Bridge (1176-1209), the work of Peter, the Chaplain of the Church of St. Mary Cole, or Peter Colechurch, as he is more familiarly known. He died four years before the bridge was finished and was succeeded by a French monk, Brother Isembert, who saw the work to its completion.

According to the eighteenth century engineer, Charles Labelye, old London Bridge had a total length of 936 feet 6 inches, and consisted of nineteen pointed arches varying in length from 15 feet to 34 feet 5 inches. No two piers had the

same dimensions, which varied from 25 to 34 feet, and two thirds of the waterway was occupied by these piers with their boat-shaped cut-waters. This constriction of tidal waters in the Thames caused rapid currents under the bridge and made "Shooting the bridge" in a boat quite a pastime for young daredevils. As medieval bridges were the natural converging place for crowds, merchants soon set up shop on the bridge, and in time it was completely covered with timbered houses and shops three-stories high. After several fires--the worst disaster coming in 1212 when three thousand lives were lost--all buildings were removed by 1756 except a chapel which remained a few years longer. Time and the increased traffic had taken their toll, and the increasing difficulty of repairing the bridge made the truth of the ditty, "London Bridge is falling down," quite apparent. Accordingly, the last vestiges of the old structure were removed and the new London Bridge (1824-31) designed by John Rennie the Elder and built by his son John, took its place among the other early nineteenth century bridges.

We still have other examples of famous bridges built or restored under the Churchmen, such as Bishop Panchielli's famous fortified Pont Valentré (1308-55) over the Lot at Cohors, France. Archbishop Tenorio in Toledo was responsible not only for the restoration of the Alcántara but for the Puente San Martin (1380) as well. However, a new class of merchants and craftsmen was gradually evolving and they began to supplant the religious builders, the character of the bridge changing from a pious work to a commercial venture. Of course, all the old bridges were not primarily pious in character as

testified by their war-like defensive towers. Many of these war bridges had narrow arches which made protection from the roadway easier when an enemy might try to assemble his boats under the bridge. The draw-bridge over the moat was another characteristic war bridge common in medieval times.

Some of the better known medieval bridges which delight modern tourists were the work of the lay successors to the Brothers of the Bridge. Lucerne, Switzerland, contains two fine examples of old wooden covered bridges over the Reuss, the Kappellbrücke (1303-33) 323 meters long with 254 scenes of the history of Switzerland by Hans Wegmann and sons (1599), and the Todtentanzbrücke (Dance of Death Bridge), originally built in 1408, rebuilt in 1568 and containing the seventeenth century Danse Macabre pictures by Kasper Meglinger. The stone Ponte Vecchio in Florence, still retaining its shape, has a long and varied history, the present bridge having been built by Taddeo Gaddi on the site of earlier Roman bridges and dating from 1345. The Czechs proudly point to the Charles Bridge at Prague as the oldest stone bridge in central Europe, its major construction period lasting from 1357 to 1414 under the architect, Peter Parlor.

In looking over these various examples of medieval work we can see fundamental similarities between most of the bridges of the period. The way in which wood was used had not changed over the centuries, and it was clear that the early medieval builders were attempting to imitate the masonry examples left them by the Romans. The art of bridge-building had not been particularly advanced by the medievalists, but at least it had been revived.

Their piers, broad and heavy, were little better than these of the Romans, and indeed were in many cases bulkier because of their liberal use of rubble. Masonry work was not as fine as that done by the Romans, and an inferior lime mortar was used. The span length of the arches usually varied from 40 to 75 feet, although there were exceptions, such as the 251-foot segmental granite arch with an 87-foot rise, erected in 1380 over the River Adda at Trezzo. Uneven arches were formed where necessary to take advantage of foundation conditions, and this led to the humping of many bridges, the highest hump resulting at the longest span. The cut-waters in most of these bridges were more pronounced on the up-stream side. One very noticeable trend in this period was the beginning of a change from the semi-circular arches of the Romans to the segmental circular arch (exemplified by the Ponte Vecchio), and to the pointed ogival or semi-Gothic type. The pointed arch especially found favor because of its adaptability to varying water levels and the ease with which it could embrace various spans. In general, the masonry arches of the period were solid concentric rings or two separated rings, the space between which was filled with rubble. In the latter part of the fourteenth century the construction of the masonry arch bridge having independent ribs supporting a flat masonry cover slab made its appearance. This was also a period where a great amount of bridge decoration was in vogue, decoration which might be religious, commercial, or war-like in nature. In contrasting the work of this or any subsequent period with that of the Romans it must be remembered that construction costs for precision work had become considerably higher

without slave labor. Be that as it may, the medieval builders did not possess the same degree of engineering skill as the Romans, and medieval works never reached the grandeur of their classical predecessors; but a start had been made and man was beginning to go forward once more.

THE RENAISSANCE -- The great revival of learning which swept through Europe from the fifteenth to the seventeenth century was more a time of ideas than of deeds. Strides in fundamental science were being made, but the practical application of the principles learned lagged far behind. This was a period when one man could still encompass the whole of knowledge, and could at the same time be a doctor, a lawyer, an engineer, and an artist. Such a man was Leonardo da Vinci who claimed to be a bridge engineer among other accomplishments, and left in his "Notitia" ample evidence in the way of sketches of his interest in this field. Another Italian, Andrea Palladio (1518-1580), having translated Vitruvius, published in 1520 his "Four Books on Architecture." Although he modestly disclaimed any credit for inventing the truss, his application of four different truss systems to bridges was the first known work on the subject. He even put his ideas into practice by constructing a bridge made of a combination of queen and king-post trusses across the Cis-mone, a span of 100 feet. Although he also designed an 8-panel king-post type and invented the trussed arch, only the simplest of his trusses were used. One early example was built over the Reuss at Bremgarten, Switzerland, in the period 1544 to 1550. However, the idea soon died, and it took almost three hundred

years for man to re-discover and utilize the truss for bridge construction.

Other thinkers of the time were also adding their contributions. In 1638 Galileo published in Leyden the first book ever written on structural analysis, "Dialoghi della Nuove Scienze." The work was grossly inaccurate in spots, but it did provide a point to start from in the analysis of stress variation in beams. Robert Hooke produced his law in 1678 on the relationship of stress to strain, and in 1680 Marriotte proved experimentally that the fibres on one side of a beam are compressed and those on the other side are extended, and he assumed that the neutral axis passed through the center of gravity of the section. Proceeding from Marriotte's Law Bernoulli in 1694 was able to calculate beam deflections. These fundamental concepts were carried forward into the next century where they were enlarged upon and eventually translated into practical application.

In the meantime the actual construction of bridges had by no means come to a standstill. In Florence Bartolommeo Ammannati, chief engineer of Duke Cosimo I, departed radically from the previous limit of a one-to-four ratio of rise to span and produced a ratio of one-to-seven in his Ponte S. Trinita (1567-1570) over the Arno. Another famous bridge of shops made its appearance in this period, the Rialto in Venice (1587-1591), the work of Antonio da Ponte. A segmental arch, greater than 88 feet in span, this bridge across the Grand Canal still plays a most important part in modern Venice. Of considerable interest is another of da Ponte's works in Venice, the arch between

the Ducal Palace and the prison--the famous "Bridge of Sighs."

Fine masonry bridges were also being produced in other countries during this period, notable contributions being the 650-foot eight-arched bridge over the Main at Würzburg, Bavaria (c 1500), the Pul-i-knaju at Isfahan, Persia, dating from the time of Shah Abbas II (1641-66), and the Pont de Pierre at Toulouse, France (1543-1632). The new bridges which arose in Paris at this time played a great part in changing her from a medieval town to a beautiful Renaissance city. The Pont Neuf (1578-1607), designed and begun by Jacques A. du Cerceau and completed under Guillaume Marchand, enjoyed a three hundred year life of useful service over the Seine despite foundation difficulties. Still standing is the Pont Royale (1685-1687), the magnificent Parisian creation of its architect, François Mansart. He was ably assisted in this work by the construction chief, Jacques Gabriel, and his foundation expert from Holland, François Romain. Here extensive dredging took place and for the first time, the open caisson with water-tight timber sides was used in placing a bridge foundation. This was also the first Paris bridge to depart from the semi-circular arch, using instead the elliptical shape.

The gradual change-over from the semi-circular to the elliptical and segmental arches was one of the great features of the Renaissance period--a period more of architectural than of structural progress. Lighter piers were adopted, lower roadway gradients were employed, and, in general, a more aesthetically pleasing bridge design was evolved. The invention of machines initiated increased efficiency in construction procedures, and

resulted in the employment of foundation piles, dredging, cofferdams, and the caisson. This period of awakening had well served to pave the way for the beginnings of engineering as a science in the eighteenth century.

ratio of about four to five. After the fall of the divided bridge Great Strides in the 18th and 19th Centuries in 1702 and completed by Perronet's design--Perronet in 1702 decided to dis-

THE MASONRY ARCH -- Modern bridge-building may be said to date from February, 1716, when the Corps des Ponts et Chaussées was founded in Paris under Jacques Gabriel (1667-1742), son of the constructor of Pont Royale. Gabriel's finest work was also the first big job taken over by the Ponts et Chaussées, the 910-foot unadorned bridge at Blois across the Loire (1716-1724). In time it became apparent that the education offered at the École de Paris was not sufficient for the needs of the Corps, so in 1747 a school for engineering draftsmen was opened. In 1760 the draughting school became the École des Ponts et Chaussées, the first engineering school in the world. Its first director was Jean Rodolphe Perronet (1708-1794), successor to Gabriel as head of the corps, and fondly known as the "Father of Modern Bridge-building." His contributions to the profession were many, for he was not only an able designer, but a capable administrator and inventor as well. Until his time, piers were constructed in such a fashion that they acted as abutments, capable of standing the thrust of each individual arch. Thus, one arch could, and would, be completely erected from one pier to the next, following which the adjoining arch would be erected. There had been examples of a divided bridge such as Gabriel's at Blois,

in which the bridge was divided into sections, each section containing three or four arches, with independent abutment piers at each section point. Such design necessarily made the piers cumbersome and heavy, resulting in a pier width to span ratio of about one to five. After the fall of the divided bridge at Mantes--which had been started by Hupeau in 1757 and completed by Perronet's Chezy--Perronet in 1763 decided to discard the use of abutment piers and use the principle that lateral thrusts of two arches meeting at a pier can be made to balance (or nearly so), leaving the pier under action of vertical loads only. This immediately reduced the pier size so that Perronet was able to erect bridges with the hitherto unheard of pier to span ratio of one to ten and even one to twelve. The first true continuous bridge utilizing this principle was the Pont de Neuilly (1768-1772) over the Seine at Paris, designed by Perronet and constructed by Chezy. It was this bridge in which the crown of one of the arches fell 23 inches after the removal of the construction support, changing the circular diameter of the arc from 320 feet to 518 feet. The practical limit of the flat arch was reached, however, in his Ponte Sainte-Maxence (1771) thirty-five miles north of Paris, where the three arches with a span of 72 feet had only a 6 foot 5 inch rise. Though hampered in his design by officialdom, this great engineer's final contribution is still a monument of civic dignity and nobility, the Pont de la Concorde, Paris (1786-1794).

Perronet had indeed revolutionized the masonry arch. In addition to the improvements noted above, he succeeded in clearing the waterway by adopting as a curve, segments of a circle of large

radius, and raising the haunches of the arch considerably. Furthermore, he replaced the old solid type of pier construction by dividing the pier into two columns connected by a lateral arch. His inventions included a mortar-mixing machine-- first used on a large scale at Neuilly--and a pump for cofferdams. The masonry arch had been known and used for centuries, but in his hand it reached perfection.

Across the channel from France English engineers were quick to follow the lead of the French in masonry construction. The pressure of public opinion resulted in a petition to Parliament in 1735 for the erection of another bridge over the Thames to assist the overloaded London Bridge. Charles Labelye, a Swiss engineer who had studied in France, was selected for the job, and work was begun on Westminster Bridge in 1738 and completed in 1750. One of the main features of the job was the use of the open-caisson method in founding the piers. The method was not a complete success, however, and it became necessary to replace the bridge with the present structure in 1862.

Agitation on the part of the public soon brought London a third bridge--the 995-foot Blackfriars Bridge (1760-1768)-- designed by Robert Milne, an Englishman, who had studied in Italy. He used nine multi-centered arches in his structure and employed the same open-caisson method in founding his piers as had been used on the Westminster Bridge. In time scour did its work on these piers, so the bridge was replaced in 1865. The next to join the stone bridges across the Thames was Waterloo Bridge (1811-1817) which lasted until 1938. Designed by John Rennie this structure contained nine semi-elliptical arches,

each with a span of 120 feet. It was described by the Italian sculptor, Canova, as "the noblest bridge in the world, worth a visit from the remotest corners of the earth." John Rennie's final design was that of the new London Bridge (1824-1831), a job which was carried to completion by his son, Sir John Rennie. With a total length of 1005 feet, the bridge had an original width between parapets of 56 feet, but this was widened to 65 feet in the period 1902-1904. As it now stands the bridge consists of five semi-elliptical arches--the largest span of 150 feet being at the center--a far cry from the old London Bridge of Peter Colechurch.

In the early days of the railroad, before iron and steel had seriously challenged stone as a structural material and before the truss had threatened the arch as a new construction principle, it was only natural that railroad-carrying bridges should be made of stone. Probably the most important of the early stone bridges in the United States was the Carrollton Viaduct (1829) over Patapsco Creek, Baltimore, designed by Benjamin Henry Latrobe for the Baltimore and Ohio Railroad. In England George Stephenson designed the Dutton viaduct (1836), consisting of twenty arches with 60-foot spans, to carry the Grand Junction Railway over the valley of ^{the} Weaver near Liverpool. Still later, in 1850, Robert Stephenson spanned the Tweed at Berwick with the Royal Border Bridge--somewhat longer than the Dutton viaduct--for the Newcastle and Berwick Railroad.

However, now that the masonry arch had reached perfection new demands were being made upon it by the increasingly heavy trains. New materials, new construction principles were needed

if progress was to continue, and from this demand evolved two factors destined to revolutionize bridge construction--the truss, and iron.

WOODEN BRIDGES -- Two Swiss carpenter brothers, Johannes (1707-1771) and Hans (1709-1783) Ulrich Grubenmann, ushered in what might be termed the modern period of wooden bridge construction. The latter began a bridge across the Rhine at Schaffhausen in 1755, wherein he covered a distance of 364 feet in two spans. Shortly thereafter Johannes put a single span of 240 feet across the Rhine at Reichenau. In 1758 they collaborated to erect a single span of 390 feet over the Limmat at Wettingen, a feat never again quite equalled in wood. Unfortunately all of these structures were burned by the French in 1799. Their works combined arch and truss principles, but the parts were too dependent on each other and the trusses were too heavy. In general, too much material was wasted, for they did not understand the true principles of the truss.

It was the United States with her large virgin forests, however, who soon led the rest of the world in timber construction. The first important bridge in this new country was the "Great Bridge" built across the Charles River at Boston in 1660. Colonel Enoch Hale, more a politician than a bridge builder, built the first framed timber bridge in the United States at Bellows Falls, Vermont in 1785, but it was replaced in 1840. During the early nineteenth century a number of bridges which were indeterminate combinations of arches and trusses made an appearance, and were to a large extent the work of

three men. Theodore Burr, a descendant of Aaron Burr, generally used the arch as an auxiliary to the truss. His bridge built in 1804 at Waterford, New York, contained four spans, the largest being 180 feet. This work was, in 1909, the oldest truss bridge in existence.¹⁹ Several of Burr's bridges were well known, but perhaps the most spectacular of them all, during its two year life, was his 360-foot arch built in 1815 over the Susquehanna at McCall's Ferry, Pennsylvania.

The second of the trio, Timothy Palmer (1751-1821) of Massachusetts, combined arch and truss action, the lower chord being cambered in many cases. His best known work was the "Permanent Bridge" (1799-1805) over the Schuylkill at Philadelphia, the final link in the Lancaster Turnpike. This bridge contained three wooden arches, the largest being 195 feet, resting on stone piers. William Weston of England designed the piers which went to a depth of almost 42 feet below high water level, an unprecedented depth at the time. Fire finally claimed the structure in 1875.

A German by birth, Louis Wernag (1770-1843) was the third of these great builders, constructing more than thirty bridges in the northeastern section of the country. He is best remembered for his "Colossus" (1812), a combined truss and arch bridge, with a clear span of over 340 feet across the Schuylkill at Fairmount, Pennsylvania. This bridge also had only a relatively short life, succumbing to fire in 1838. Wernag's work showed a combination of relatively heavy arches and light trusses, acting somewhat on the same principle as a stiffened suspension bridge, but with the cable inverted to form an arch in compression.

During this same period a certain amount of important building in timber was going on in Europe. In England Robert Stephenson, Isambard Kingdom Brunel, and Joseph Locke were engaged in the construction of railroad bridges. Carl Friedrick Wiebeking (1762-1842), the director-general of bridges and roads in Bavaria, erected several structures, all arches, the most important one being over the Regnitz at Bamberg (1809), with a span of 206 feet and a rise of 16 feet. Emiland Marie Gauthey (1732-1806) is best remembered for his trussed arch over the Saone at Lyon, made of straight members only, spanning 164 feet. In general, the Europeans were favoring the arch, the form they had used so long in stone, so it remained for the Americans to develop this "new" construction principle, the truss.

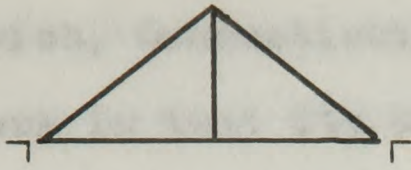
THE TRUSS -- The rise of the railroads about 1830 stimulated a tremendous interest in bridges. In Europe the main line of evolution was in the metal girder, but in the United States interest focussed on the truss--first in timber, then in iron, and finally in steel. Although the truss--which can be defined as a framework whose members are so arranged that they are subject only to longitudinal stresses of tension and compression--was used by Palladio as early as the sixteenth century, it had little or no influence until it was rediscovered and used by Theodore Burr early in the nineteenth century. His truss may be called the parent of all other trusses developed in the United States. Because of her tremendous wealth in timber, it was natural that the United States should develop a structural type such as this, suited to the peculiarities of wood. A certain

amount of credit for the development in America must go to John Rennie who advised Professor Robinson on the theory of structures, when the latter was writing for the Encyclopaedia Britannica. This theoretical source of great importance was first published in 1798, and the American supplement appeared in 1803. Another early theoretical effort appeared in 1811 when Thomas Pope, a shipbuilder, wrote the first American "Treatise on Bridge Architecture."

Although most of the fundamental principles of the truss were evolved during the first half of the nineteenth century, the great strides in practical development were made in the second half of the century. In 1820 a New Haven architect, Ithiel Town, patented an indeterminate lattice truss which was used as early as 1821 and was popular in New England for many years. The main feature of his invention was the fact that it could be of sawed planks rather than of heavy hewn timbers. One of the best known bridges of this type was the 2900-foot railroad bridge over the James River at Richmond, Virginia, with individual spans as great as 153 feet.

Lieutenant Colonel S.H. Long of the U.S. Army patented a truss in 1830 which was uniform in depth with cross bracing in each panel. By 1839 his truss had evolved into an all wood version of the Howe truss, patented by William Howe of Spencer, Massachusetts in 1840. Howe made his vertical braces, which were in tension, of round wrought-iron bars with screw ends. His first bridge was erected at Warren Village, Massachusetts, in 1838, and like Long's invention, had counter as well as main struts.

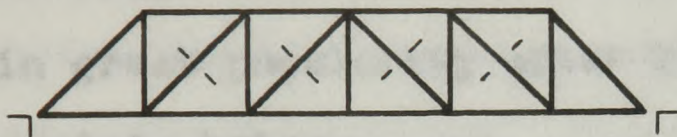
TRUSS TYPES



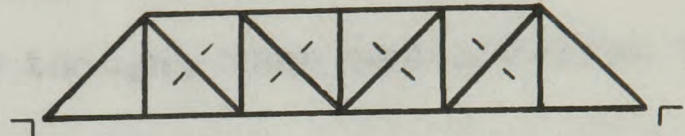
King-post



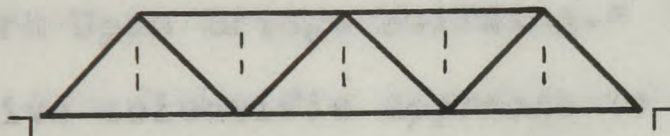
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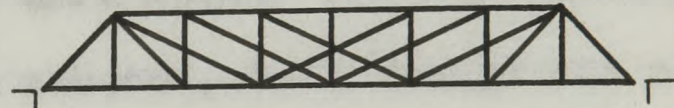
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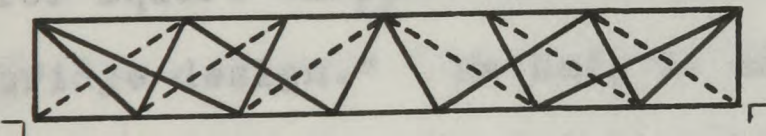
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Warren



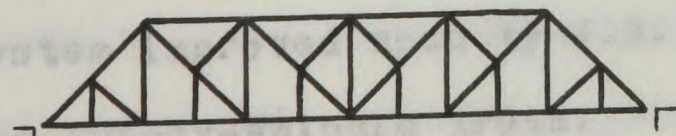
Whipple



Post



Bollman



Baltimore



Lattice



Parker



Fink

Fig. 4

The Pratt truss was patented in 1844 by a father and son combination, Caleb and Thomas W. Pratt of Boston, Massachusetts, and Norwich, Connecticut, respectively. It differed from the Howe truss in that its diagonals were in tension and were therefore of iron, all other parts being of wood. It never reached any degree of popularity in this composite form, however, for iron diagonals were less economical than iron verticals. It did gain great popularity after 1850 though, when the all-iron truss came into being.

In 1847 at Utica, New York, Squire Whipple published the first treatise for calculating stresses in trusses entitled, "A Work Upon Bridge Building." His work opened the way for a positive scientific approach to the subject, took design out of the hands of the purely "practical" men, and placed it in the hands of capable bridge engineers. Small wonder that this work won for Squire Whipple the title of "Father of American rational bridge design." He had, in addition, been quite active in designing trusses and building bridges himself, one of his best known being a 146-foot span near Troy, New York (1832). He was the first American to use the double intersection web system, a system improved upon by J.W. Murphy and known for many years as the Murphy-Whipple truss.

The universal need at this time for more rational bridge design is illustrated by the fact that other engineers were, quite independently of Whipple, thinking and writing along the same lines. Robert Bow of Edinburgh wrote a "Treatise on Bracing" in 1850. In 1851 Herman Haupt published in New York "The General Theory of Bridge Construction", and in England at about

the same time, William T. Doyne and William B. Blood produced "An Investigation of the Strains upon the Diagonals of Lattice Beams with Resulting Formulae."

Along with increased theoretical knowledge came bigger trains, better iron, and more demands on bridges. Engineers employed by the railroads were constantly developing new types of trusses to meet their particular problems in the field. In London the Warren truss was patented in 1848 by James Warren and Willoughby T. Monzani. It was claimed that a Belgian engineer, Neuville, had built Warren type trusses across the Lye west of Ghent in 1846, but the first of the type to come out after the patent had been granted was the Newark Dyke bridge, with spans of 259 feet, for the Great Northern Railway in Britain.

The Baltimore and Ohio Railroad had two field engineers, both of whom developed different truss types in 1852 while working under the same chief engineer, Benjamin H. Latrobe. Wendell Bollman spanned 124 feet at Harper's Ferry and Albert Fink was responsible for the three 215-foot spans over the Monongahela at Fairmount, West Virginia. In 1865 S.S. Post produced a truss in which the compression members inclined at an angle were supposed to give the greatest economy of material to the web system. This type only enjoyed popularity for about fifteen to eighteen years. Modifications of older types were constantly being made as the railroads fought for more economical methods of doing larger jobs. In the 1870's C.H. Parker modified the Pratt truss by making the top chords on through bridges polygonal, thus saving weight on long spans. The Pennsylvania Railroad originated the Baltimore truss in 1871 by subdividing the panels of

the Pratt truss; when the top chords were made polygonal by the company, the design came to be known as the Pennsylvania truss. Both of these latter types also became known as the Petit truss.

It was only natural that the development of so many different kinds of trusses would lead to a competition, more economic than structural, the result of which would be the elimination of many from the field. The Whipple truss died because it was found more economical to support floor beams by short sub-verticals attached to a single system of bracing than by use of a double system, and because a single system is more reliable and determinate in respect to stresses. The Bollman and Fink trusses went out because of their uneconomical method of transferring load directly to the abutments. Regardless of the type, however, the nineteenth century truss in some form had come to stay.

EARLY IRON ARCHES, TRUSSES, AND GIRDERS -- Unknown as a structural material at the beginning of the eighteenth century, iron in its cast form came into general use during that century. Wrought-iron structural beams were known by the end of the century but did not come into general commercial use until about 1850. While the earliest iron beams assumed the shape of the dressed logs they replaced, it was soon realized that beam depth was the controlling factor, and the development of the flange and web type of beam was the natural result. Cast-iron beams in the T, U, and channel shapes were available in England prior to 1840, but were unsatisfactory for bridge construction on account of the low tensile strength and general unreliability of the metal. Wrought-iron rails for the railroads were produced

as early as 1820 and by 1875 15-inch I beams were obtainable commercially. Extensive use of cast iron in bridge construction disappeared after 1850 in favor of wrought iron, which led the field until challenged and overtaken by medium steel about 1890.

Although an iron arch was cast at Lyons in 1775, it was never erected, so the honor of being the first successful iron arch bridge fell to the Coalbrookdale Arch (1775-1779) in Shropshire, a bridge which still stands. The proprietor of the coal-iron works, Abraham Darby III (1750-1791), and his associate, John Wilkinson (1728-1808), having decided to replace the ferry over the Severn, engaged the architect, Thomas F. Pritchard of Shrewsbury. The structure was made of five semi-circular iron ribs cast in 70-foot halves, spanning 100 feet. Shortly thereafter, in 1783, iron was first rolled to structural shapes by Henry Cort at Fontley, England, thus pointing the way to future economical construction in iron. The second iron bridge, designed by Thomas Telford, was erected in 1796 at Buildwas, about three miles from the Coalbrookdale structure. Telford built up his arch using cast-iron blocks as voussoirs in the same fashion as was customary in masonry construction. This structure which was longer than its predecessor in iron used only half as much iron and lasted 110 years.

Thomas Paine of political fame designed some long cast-iron arches in 1786 to be used for a bridge over the Schuylkill. The metal was cast by Messrs. Walker in Yorkshire but was never shipped to America, for Paine had lost his financial backing and had, in turn, become interested in the French Revolution. The

arches were later used (1796) by Rowland Burdon in the Sunderland Bridge--a 236-foot span over the Wear at Wearmouth, England.

The lead taken by England in the iron construction field was soon followed by other countries. In 1796 the Royal Iron Works of Malapane cast a 60-foot span still in use over the Striegauer Wasser near Laasan in Lower Silesia. At Paris in 1803, de Cessart directed the construction of the Pont du Louvre, a light footbridge of nine spans of 57 feet each. Captain Richard Delafield (1798-1873), of the Army Engineers, constructed the first iron bridge in the United States over Dunlap's Creek at Brownsville, Pennsylvania (1836). This 80-foot span was another link in that great highway, the Cumberland Road.

When men first began building with iron, they built voussoirs, imitating the masonry arch which had been used for centuries. As they grew more familiar with this new structural material, they developed new types of construction. Telford's 150-foot cast-iron bridge over the Spey at Craig-Ellichie, Scotland, with its two concentric ribs fastened together by diagonals became the first modern trussed arch and spandrel. The first arch span of monolithic type was the wrought-iron footbridge over the River Crou at St. Denis in 1808. Then the appearance of the steam engine brought new aid and new problems. New types of machines which aided construction were brought into play. On the other hand, a new type of transportation, the railroad, had come into being, and with it, the demand for heavier loads and greater speeds, meaning sturdier bridges.

As noted before, the truss was a partial answer to the

railroad problem in the United States. R.B. Osborne, the chief engineer of the Reading Railroad Company, designed the first iron truss railroad bridge, a combination of wrought and cast iron. Constructed as a Howe type in 1845 it remained in use over a stream near Manayunk until 1901. While the truss was largely an American development, its use was well known in England, the first iron truss of magnitude being the Newark Dike Bridge (1851-1853) over the Trent. Designed by C. Wild and built by J. Cubitt, this 259-foot Warren girder was built to carry the Great Northern Railroad. John H. Linville of the Pennsylvania Railroad is remembered for his long span truss bridges, the Steubenville Bridge (1863-1864) over the Ohio with a central span of 320 feet being one of his finest. As with other bridge types the span of the simple truss continued to increase with the years, reaching a climax in 1894 with the 546-foot, 6-inch Louisville and Jefferson Bridge over the Ohio River.

Another logical development in iron was the girder. George Stephenson (1781-1848) and his son Robert (1803-1859), were pioneers in this field, having played a large part in ushering in the railroad era. Their first bridges were arches, but in 1829 George erected a single cast-iron beam as a lintel over Water Street in Manchester for the Liverpool and Manchester Railway. The arched beam or bowstring girder held together by horizontal ties was the next step, and Robert built several of this type. Probably his finest was the double-decked High Level Bridge (1846-1849) over the Tyne between Newcastle and Gateshead. Aside from its structure, notable for the time, this bridge was

also distinguished by the fact that the driving of piles by steam was used in the construction of its piers--the first steam driven piles in the history of bridge construction.

Young Stephenson's crowning achievement, however, was the Britannia Bridge (1846-1850) carrying the London and Holyhead Railway across the Menai Straits in North Wales. His original idea was to create a stiffened suspension bridge, but experiments showed that suspension chains could be omitted, leaving only the immense tubular beam. He had called in William Fairbairn, the owner of a shipbuilding works at Millwall, London, and Professor Hodgkinson, a mathematician, to advise and assist him on many points of this bridge, and it may be said that they had a great influence on the final decision to discard cast iron and to use wrought iron exclusively, a practice which was generally adopted throughout the bridge-building industry until the advent of steel. In its final form the bridge consisted of two rectangular hollow tubes of wrought-iron plate placed side by side, each 1511 feet in length, 15 feet in width, varying from 23 to 30 feet in depth, and weighing 4680 tons. Resting on two abutments and three towers this arrangement resulted in two spans of 460 feet each, and two, of 230 feet each.

Although the Britannia Bridge still stands and serves the public well, the unnecessarily heavy and therefore expensive tubular bridge type never did achieve great popularity. The Conway Bridge, opened in 1848 a few miles east of Stephenson's Britannia Bridge, was a smaller version of the same type. It was Robert Stephenson again who designed the longest tubular bridge in the world, the Victoria Bridge over the St. Lawrence

at Montreal. Completed in 1860 it took the constructor, Alexander McKenzie Ross, six years to complete the 6600-foot tube. Stephenson's final contribution to this type was a span over the Nile, near Damietta, in lower Egypt. With Robert Stephenson the tubular bridge passed into history, possibly to be revived at some future date should new materials make such a type economically feasible.

In the meantime, William Fairbairn, Stephenson's associate, had experimented extensively with riveted wrought-iron beams. It is possible that he was first in this field for he used these beams in the floors of buildings as early as 1831. The first all wrought-iron highway bridge made its appearance over the Pollock and Govan Railroad near Glasgow in 1841. Fairbairn and the younger Stephenson patented in 1846 a plate girder with square tubes for the top chord. In the same year James Millholland in the United States erected a 50-foot riveted girder for the Baltimore and Susquehanna Railroad near Bolton Depot. From then on the utilitarian plate girder became standard for short railroad spans.

The ascendancy of wrought iron revived arch construction to a certain extent. In 1853 the first bridge to carry the Swiss Central Railroad over the Aare River at Olten consisted of three 105-foot wrought-iron arch spans. Another arch was erected over the Rhine at Constance in 1862, and in 1864 three spans of 317 feet each were erected at Coblenz. The simple arch soon passed out of the picture, however, and composite types arose, more suited to the economic use of steel which was soon to replace wrought iron.

SUSPENSION BRIDGES -- Although primitive suspension bridges had been known for centuries, the development of structural materials with sufficient tensile strength had been too slow to permit this type of bridge to compete with the beam and arch types. The development of iron heralded the development of the suspension bridge. The first modern authentic structure of this type was a crude iron chain bridge (1741) across the River Tees in England, a 70-foot span with the flooring resting directly on the cables. Toward the end of the eighteenth century an American judge and justice of the peace, James Finley of Fayette County, Pennsylvania, became interested in the possibilities of suspension bridges, and before two decades had passed in the nineteenth century he had built some forty "chain" bridges. He first produced the suspended stiff level floor in 1801 in his 70-foot span over Jacob's Creek but did not patent the idea until 1808.

In 1810 John Templeman built a Finley-designed bridge over one channel of the Merrimac River above Newburyport, Massachusetts. Although the span was rebuilt in 1909, this bridge still retains its original form, the distance between towers being 244 feet. It is interesting to note that in the original construction the chains, which were 516 feet long, were painted to ward off rust. To Finley also goes the credit for constructing in 1811 the first suspension bridge of more than one span, a 475-foot bridge over the Lehigh River near Northampton, Pennsylvania, consisting of two whole and two half spans.

In the same year Sir Samuel Brown (1776-1852), a Captain in the Royal Navy, proposed the use of flat bars or links

instead of the round or square bars then used. His 449-foot Union Bridge over the Tweed at Berwick built in 1819-20 was his greatest work and was the first important suspension bridge in Great Britain. Meanwhile another idea gained momentum, the use of wire instead of chains. Probably the first use of wire in this manner was made by Josiah White and Erskine Hazard in 1816, when they erected a narrow footbridge 18 inches wide, stretching 408 feet over the Schuylkill at what is now Fairmount Park, Pennsylvania, for a reputed cost of \$125.00.

Chains remained the favorite in Europe for almost another twenty years, however. Marc Séguin, an early leader in the development of the suspension bridge in France, constructed his first bridge near his factory in Annonay, Ardeche. In 1825 he and his brothers put a private toll bridge over the Rhône between Tain and Tournon, from which the family collected tolls for 99 years. Another Frenchman, Louis Marie Henri Navier (1785-1836), inspired by his trip to England in 1821, advanced the theoretical side by publishing about 1824 the first book on suspension bridges.

No story of suspension bridges is complete without reference to Telford's Menai Bridge (1819-1826) carrying the Holyhead Road over the Menai Straits. It has rightfully been called the grandfather of modern suspension bridges with its over-all length of 1710 feet, and distance between supports of 579 feet. Telford ran hundreds of tests on wrought iron before completing his design, and then insisted that every piece of iron for the cables be likewise put to test. His meticulousness was rewarded by the production of a bridge which lasted faithfully until

recent times when it was reconstructed to take care of increasing traffic.

Two years after the opening of the Menai Bridge puddled steel eye bar chains were used by the engineer Von Mises in his 312-foot chain suspension bridge over the Danube at Vienna--the first recorded use of steel in bridge construction. One of the most famous chain bridges of this era was W.T. Clark's Kettenbrücke (1839-1845) over the Danube at Budapest, a 663-foot span which still stands.

As we have noted, however, wire was gradually succeeding chain. A great construction step was taken by the Frenchman M. Vicat in 1829 when, in constructing a bridge over the Rhône, he developed the method of stringing cable in place in the air instead of building it on the ground and then transferring it to the towers. Another forward step was taken three years later by James Dredge, who introduced stiffening to the roadway of his suspension bridge at Loch Lomond. The first wire suspension bridge of consequence in Europe was the Pont du Gotteron over the Sarine at Fribourg, erected in 1834 by Joseph Chaley. Each cable was composed of more than a thousand wires bound together with wire wrapping and the span between points of cable supports was 870 feet.

Other wire suspension bridges were built during the next few years, but the first engineer of great repute to adopt this system was Colonel Charles Ellet (1810-1862) of Pennsylvania. His first large suspension job was the replacement of Wernag's "Colossus" in 1841-42 with a 358-foot span. Probably his greatest work was the 1010-foot span over the Ohio River at Wheeling,

West Virginia, the longest span of its day. Erected in 1848 it was damaged by a tornado five years later, and was then repaired by John A. Roebling.

Up to this time the flexibility of the suspension bridge made its use impractical for railroads. However, interest in bridging the ^aNiagara River between the Falls and the Whirlpool spurred the imagination of engineers to whom the suspension type seemed the most practical answer. Colonel Ellet set out to do this job in 1848, but differences between the engineer-contractor and the directors resulted in his resignation from the project. John A. Roebling then took up the work and built what might be termed the first true stiffened suspension bridge (1851-1855). When Roebling first announced his intention of building a railroad suspension bridge, he received from Robert Stephenson of Britannia Bridge fame a letter stating: "If your bridge succeeds, mine is a magnificent blunder." His span, slightly greater than 821 feet, was a success due to his use of 16-foot deep stiffening trusses of timber posts and wrought-iron diagonal rods. A double-decked structure 24 feet wide and 245 feet above the rapids, this bridge contained a highway between its trusses and a single track railroad above. It was finally displaced in 1897 by a double-track spandrel traced arch.

Roebling was not alone in his dream of a stiffened suspension bridge. Among the first to propose large open-web stiffening trusses was John C. Trautwine, but none of his designs ever reached the construction stage. W.J.M. Rankine in his "Applied Mechanics"⁽¹⁸⁵⁸⁾ proved that the necessary strength of a stiffening girder would be only one-seventh part that of an independent girder of the same span as the bridge, suited to carry the same

moving load. An Englishman, P.W. Barlow, is generally credited as being among the first to use Trautwine's suggestions in his Lambeth Bridge over the Thames (1862). And so the groundwork was laid for the most important suspension bridge of the century, the Brooklyn Bridge.

CANTILEVER BRIDGES -- While during the nineteenth century the truss and suspension bridges were undergoing unprecedented development, the cantilever type was evolving more slowly, its main recommendation being that no falsework was required for its erection. The first modern suggestion concerning this type was made by Thomas Pope in "A Treatise on Bridge Architecture" (1812), but it was not until 1867 that the first modern cantilever was actually erected. The work of Heinrich Gerber, this bridge was erected over the Main at Hassfurt, Bavaria, a three-span job with a central opening of 425 feet. For many years thereafter the cantilever bridge was known as a "Gerber" type.

The first use of this type in railroad work was made in 1876 when a five-span bridge was erected at Posen, Poland. In the same year the first important cantilever appeared in the United States carrying the Cincinnati Southern Railroad over the Kentucky River at Dixville, Kentucky. Designed by Charles Shaler Smith, this bridge contained three equal spans of 375 feet each.

A radical departure from having the cantilever arms meet at the center of the span was employed by C.C. Snieder in 1883 in his Michigan Central Railroad Bridge over the Niag^ara River. Here the cantilever arms supported a central section designed

as a simple truss, thus forming the first suspended-span cantilever. For the first time the name "cantilever" was applied to this type of structure, and it marked the initial attempt in the United States to vary the depth of the cantilever arms. A step forward in span length was recorded here with a main central span of 495 feet. But it merely indicated the potentialities of the type, for the construction of the monumental Firth of Forth Bridge had already begun.

The Age of Steel Begins - the Latter Half of the 19th Century

DISASTERS -- As bridge builders centuries before him had done, the nineteenth century engineer learned how to build with new materials by observing his failures, seeking the reason for those failures, and then improving with experience. During the 1870's and 1880's truss bridges on American railroads failed at the

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rate of twenty-five a year. One of the worst disasters occurred at Ashtabula, Ohio, in 1877 when a wrought-iron Howe truss built by Amasa Stone twelve years earlier failed, resulting in the loss of ninety lives. Factors in the failure were the high dead load, the insufficient diagonal bracing in the truss, and the nature of the iron itself--all the result of insufficient knowledge concerning wrought-iron under tensile strain. The failure did have its benefits, however. From that time on the railroads completely eliminated cast iron (though cast iron was not named as a cause of failure in this case) as a structural material on bridges. They also decided that henceforth they would call in bridge specialists, a factor which led to the establishment of

many private firms specializing in the design and construction of bridges alone. Two years later thirteen spans of the Firth of Tay Bridge collapsed, carrying a train load of a hundred people to their deaths. Composed of eighty-four 200-foot wrought-iron truss spans resting on cast-iron cylinders, this product of the eminent Sir Thomas Bouch was one of the last of the great iron bridges. The main criticism levelled at the designer at the time was his failure to design adequately for wind load.

These and many other disasters meant that man would have to find a lighter, stronger material if bridge-building was to progress. Soon the answer was clear--steel.

BEGINNINGS OF STEEL -- Before 1856 the prohibitive cost of steel restricted its use to small items such as edged tools.

In that year the Englishman Henry Bessemer (1813-1898) introduced his converter which revolutionized the manufacture of steel, and made structural steel shapes an economic possibility.

Shortly thereafter, Pierre Émile Martin (1824-1915), a Frenchman, cooperated with a German living in England, Charles W. Siemens (1823-1883), to develop and patent the Siemens-Martin open-hearth process for making steel. In 1867, Siemens

produced rolled steel rails, thus marking the beginning of the commercial manufacture of structural steel members.

Improvements in manufacture accompanied the passing of years, so that between 1880 and 1890 a more economical method of eliminating carbon and silicon from pig iron became general commercially. Initially steel was employed in eye bars for tension

members, then for webs in floor beams, and by 1890 various shapes such as angles and channels were available. By 1900 steel had replaced wrought iron, for it was selling at the same price as the iron but was from ten to fifteen percent stronger.

As we have noted, steel had been used in bridges early in the nineteenth century, but the first all-steel bridge did not emerge until 1878-79. Composed of five truss spans of 315 feet each, this bridge was built by General William Sooy Smith to carry the old Chicago and Alton Railroad over the Missouri River at Glasgow, South Dakota. His decision to use steel was due largely to the influence of one, A. Hay of Burlington, Iowa, who had developed a new inexpensive manufacturing process for "Hay Steel." Smith's confidence in the steel was justified, for the bridge stood for several years before it was replaced by a heavier structure. But let us turn back the clock a few years to examine a bridge which, though not all of steel, may be said to have opened the Age of Steel in bridge-building.

lift and eject the material from the caissons.

THE ST. LOUIS BRIDGE. -- For many years the bridging of the Mississippi River had stood as a challenge to the foremost engineers of America. Plans for accomplishing the job at St. Louis had been advanced in 1839 by Charles Ellet, in 1855 by Josiah Dent, and in 1856 by John Roebling, but it remained for Captain James Buchanan Eads (1820-1887) of Lawrenceburg, Indiana, to transform the dream into a reality. His three magnificent steel arches--a span of 520 feet flanked on either side by a span of 502 feet--were erected as cantilevers without the use of falsework. While Eads used iron along with the steel in the trusses, this

work, actually begun in 1867 but "officially" begun the next year and completed in 1874, marked the first extensive use of structural steel in bridges.

Another notable feature of this structure was the use of the pneumatic caisson in the foundation work, making this bridge one of the first two in the country to benefit by the method. The pneumatic caisson was by no means a new idea, but it had been suggested as early as 1647 by the physicist Papin and again in 1779 by the French engineer Coulomb. It was first applied to bridges by John Wright at Rochester, England in 1851 and by 1860 its use was common knowledge throughout Europe. Eads brought back the idea of this air-tight box and proceeded to improve upon it, establishing a new depth record in founding his east abutment 103 feet below normal water level, or 136 feet below high water. He tackled the difficulty of cutting down through more than 80 feet of gravel, sand, and silt by inventing the "sand pump" which utilized a high pressure flow of water to lift and eject the material from the caisson.

The bridge had other claims to fame, such as being the longest hingeless, fixed-end metallic arch in the world. The use of hollow tubular chord members was another praiseworthy innovation. Andrew Carnegie, writing in later life, gave credit to his connections with this bridge for starting him out on his career. Of greater significance was the spur the bridge gave to transcontinental railroad systems, thus aiding in the expansion of the West and in transforming St. Louis into a city of the first magnitude. Captain Eads, with his courage and vision, had done more than to merely span a river, he had

helped to span a continent. ~~It was the largest~~
~~and most successful, Roebling's suspension bridge, ever~~
THE BROOKLYN BRIDGE -- For fifty years people had talked about connecting Manhattan and Brooklyn with a bridge, but nothing concrete was done until John A. Roebling (1806-1869) was called for the task. Born in Germany and educated at the Royal Polytechnic School in Berlin, Roebling had migrated to the United States as a young man, and soon achieved fame as a bridge engineer of the first order. He had scarcely finished the 1057-foot span over the Ohio at Cincinnati when he was appointed chief engineer for the Brooklyn Bridge in 1867. He threw himself into the project with enthusiasm, overcoming all professional and political obstacles, until actual construction was begun in 1869. Fate denied him the pleasure of seeing his vision fulfilled, however, for during the early weeks of construction he died as the result of injuries received on the Brooklyn Wharf, where he was making surveys for the location of the main piers.

His place was taken by his son, Colonel Washington A. Roebling (1837-1926), a graduate of the first engineering school in the United States, Rensselaer Polytechnic Institute. Young Roebling, well versed in his father's methods, directed the gigantic task to its successful completion despite the fact that he was permanently paralyzed by the dread caisson disease while working on the foundations in 1872.

Finished in 1883, after a construction period of fourteen years, this fine structure represented a great step forward in suspension bridges. Not only was this the first suspension bridge to use cables of steel wire, but its central span of

1595½ feet was greater by almost fifty percent than its largest predecessor, Roebling's Cincinnati Bridge. With side spans of 930 feet, a width of 85 feet, and a length of 5989 feet overall it was a mammoth in its day. Sea-faring men note with interest its clearance of 135 feet above the water line, a figure arrived at by a board of three army engineers and destined to become standard for U.S. bridges over navigable waters, thus fixing the maximum height of U.S. men-of-war for the greater part of a century. While the first crude modern theories on suspension bridges came too late to influence the design of the Brooklyn Bridge, it still stands as mute evidence of a successful design created by experience, intuition, and genius.

THE FIRTH OF FORTH BRIDGE -- Last but not least of the great bridge trio which closed out the nineteenth century was the gigantic cantilever Firth of Forth Bridge (1882-1889). As with other great bridges, proposals for erection preceded actual work by many years. In 1818 James Anderson of Edinburgh proposed a suspension bridge of three main spans, but the proposal never went beyond the design stage. Sir Thomas Bouch had received approval for a two-span suspension bridge in 1873, and had actually begun construction when the Firth of Tay Bridge disaster destroyed public confidence in him and wrecked his career.

The job then fell into the hands of two noted engineers, both of whom had served their apprenticeships in southern England, Sir John Fowler (1817-1898), and his partner, Sir Benjamin Baker (1840-1907). Rendered cautious by Bouch's failure,

the designers created an awe-inspiring heavy structure calculated to withstand a wind pressure of 50 pounds per square foot on exposed surfaces, a figure which has been reduced to 30 pounds in most modern designs. Practically the whole superstructure was made of steel, a bold adventure considering that the use of steel in bridge-building was prohibited by the English Board of Trade Regulations as late as 1877.

The construction of this bridge ended the experimental period and established the cantilever as an accepted modern type. Extending over a mile in length with a clear heading above the water of 157 feet, the bridge contains two main spans of 1710 feet each, with six cantilevers of 680 feet each, and two suspended girders of 350 feet. While no longer the longest cantilever in the world, the structure remains a high point in the annals of engineering--a colossal giant astride the Firth of Forth, a rugged symbol of the country it serves, Scotland.

19th CENTURY PROGRESS -- We have noted how the masonry arch had reached perfection under the hand of Perronet by the close of the eighteenth century, and how it was superseded by iron and the truss as railroads grew. Although the use of the arch was limited for several years, it was never forgotten, and then it came back as strong as ever, this time in steel, in Captain Eads' St. Louis Bridge. New theories on arch action were being evolved, and in 1879 Weyrauch demonstrated the fundamental equations on which the elastic arch theory is based, the universally accepted theory today for arch analysis.

The truss had undergone a startling development in the

United States. During this growing period trusses were designed by competing bridge-fabricating companies where accent was laid on cheapness and facility of erection--neither point being particularly conducive to longevity or architectural beauty. It was difficult to check the extravagant claims of the companies for no full size tests on their structures had been made and testing machines had not come into general use. As the century drew to a close, however, the industry began to settle down and good specifications governing materials, fabrication, erection made their appearance. One of the leaders in this field was George S. Morison, a Harvard Law graduate, whose specifications were adopted as standard for U.S. railroad bridges, and thus had great influence on subsequent construction throughout the world.

The suspension and cantilever bridge types had also made great strides, resulting in the Brooklyn and Firth of Forth Bridges. Materials too were being changed. The early development in Europe had been with masonry, whereas in the United States wood was the material most widely used until 1840. Cast and wrought iron were used jointly, the wrought iron becoming more predominant every year, until about 1877 when cast iron was discarded almost completely. Steel made its first extensive appearance in 1874, was quite common by 1890, and had practically eliminated wrought iron by the turn of the century.

In the theoretical field man was also forging ahead. The investigators of the seventeenth century, as we have noted, had passed a valuable heritage on to their successors of the eighteenth century, and this work was in turn passed along. In 1713

Parent advanced the theory that the neutral axis and center of gravity of a beam coincide, a theory re-affirmed by Coulomb in 1773. In 1744 Euler developed his column formula based on Bernoulli's findings, and in the early nineteenth century Lagrange and Navier extended the work. Then began the period of dissertations on simple bridges and trusses prevalent in the first half of the nineteenth century. In the latter half of the century more advanced scientific and mathematical work was accomplished, especially in Europe. The "Theory of Equilibrium in Elastic Systems and their Applications" (1879) was written in French by the Italian, Professor Castigliano, the first work of consequence on indeterminates. Manderla in Germany published a highly scientific and mathematical paper on secondary stresses in 1880, but it was not until 1905 that the first work on this subject appeared in English--the work of Professor Hiroi of the Tokyo Imperial University. The Tay Bridge disaster brought forth many studies on wind bracing, the more important among them being A.S. DuBois' "Graphic Statics" (1875) and "Stresses in Framed Structures" (1883); Merriman and Jacoby's "Roofs and Bridges" (1886); and Johnson, Bryan, and Turneaure's "Theory and Practice of Modern Framed Structures" (1893).

Practice in the United States had strayed too far from the theoretical side and had become groping and commercialized, a fact which many in the profession realized. Accordingly, there began a steady stream of students from America to Europe, especially to Germany, continuing on into the early part of the next century. In the meantime engineers in the construction field had begun to work out standardized procedures which were

to bring greater economy, strength, and beauty to their structures.

During the nineteenth century the mathematician had developed formulae for the analysis of framed structures, the metallurgist and mechanical engineer had produced a steel suitable for structural members, and the bridge engineer had become familiar with the practical aspects of truss design and erection--thus was consolidated a team destined to make the twentieth century a golden age in bridge-building.

The Twentieth Century

MOVABLE BRIDGES -- The simple lift or drawbridge dates back to Roman days at least, but most of the development of the moving bridge is modern. General types in use today include the swing bridge, a horizontal plane turning about a vertical axis; the trunnion bascule bridge, of one or two leaves elevating about a horizontal axis; and the rolling lift or bascule bridge, where the leaves roll into a vertical position with the land end rolling on smooth track.

One of the best known bascules is London's Tower Bridge (1886-1894) with a central span of 200 feet. Very few tourists sighting this famous landmark are aware of the fact that the two masonry towers they see simply cover steel towers which house the hydraulic machinery. Another bridge of note is the Burlington-Bristol highway bridge which crosses the Delaware south of Trenton, New Jersey. Its 534-foot movable span won for it the reputation of being the longest highway lift bridge in existence.

When lowered, its main and end spans look like a continuous truss. By virtue of a vertically lifting section of 544 feet, the Buzzard's Bay Bridge--carrying the New York, New Haven, and Hartford Railroad across the west end of the Cape Cod Canal--was enabled to claim the distinction of being the longest lift span in the world.

REINFORCED CONCRETE BRIDGES -- A twentieth century product, the reinforced concrete bridge may still be regarded as being in an infant stage. The builder's first impulse was to imitate stone with this new material, so early bridges naturally took on the shape of the arch. Thus the first reinforced concrete bridge built in the United States was a 20-foot arch at Golden Gate Park, San Francisco (1889). Most of the developments since that time have been on highway bridges, but not exclusively so. In 1915 the Lackawana Railroad built one of the greatest of the concrete bridges, the Tunkhannock Viaduct (total length 2375 feet), consisting of ten 180-foot visible arches and two 100-foot covered spans. One of the most famous of the highway bridges in the United States is the George Westinghouse Bridge, the work of N.F. Brown and V.R. Covell. Spanning Turtle Creek Valley east of Pittsburg on the Lincoln Highway, the bridge consists of five arches--the center one being 460 feet--which go to make up a total length of 1510 feet.

However, the leaders in the field have been the Europeans, who have designed and built some remarkable and beautiful structures. Typical of that excellence is the Plougastel Bridge (1930) over the Elorn River at Brest, France, designed by M.

Freyssinet, a leading exponent of long span reinforced concrete arch construction. His three spans of 612 feet each held the world's record for length in this type until 1940 when the 645-foot arch at Elsa, Spain was completed. In Switzerland the late Robert Maillart was responsible for many bold arches in the "International Style." The Swedes have also been active in this field, as testified by their 593-foot 5-inch Tranberg Sound Bridge. Fifty miles up the Dnieper River from the Dnieprostroy power plant the Russians began a bridge under the Czar and finished it under the Soviets in 1932--a 5350-foot bridge, 4600 feet of it being in concrete.

It might be well to note here that the masonry arch has not passed completely out of the picture as a result of the introduction of new materials. The largest masonry arch to date is modern, the Adolphe Bridge (1900-1903) in Luxemburg, with a span of 278 feet, a rise of 102 feet, and a width greater than 52 feet. Two and three hinged arches of masonry have been built since 1900 in the United States and Germany. One of the new innovations has been the hinge used by Leibbrand of Stuttgart, a one-inch lead sheet extending over the middle third of the depth of the voussoir joints. The possibilities for improvement in the masonry arch are so slight though, that it is very unlikely that it can ever offer serious competition to the new types which have evolved as the result of the introduction of new materials.

Whether man-made masonry, concrete, can offer that competition is a question which must be answered in the future. For certain small spans it is economical, in other cases it has its architectural advantages. Perhaps its future lies in some

other form than the arch, a form which will better express the function of concrete--only time will tell.

MODERN STEEL ARCHES -- No great steel arches made their appearance from Captain Eads' time until 1907, when Sir Douglas Fox completed the Victoria Falls Bridge over the Zambesi River. Designed to carry the railroad connecting South Africa with Egypt, its total length was 650 feet with an arch span of 500 feet. Hovering over a 400-foot gorge, it held the distinction of being the highest bridge in the world at the time, a title since taken by the 880-foot suspension over the Arkansas River, the Royal Gorge Bridge (1929), 1050 feet above the stream.

The next arch of importance was the Hell Gate Bridge (1916) over the East River at New York City. It was the greatest creation of that famous engineer, Gustav Lindenthal (1850-1935), who had been born in Moravia (then Austria) and had migrated early in life to the United States. The greater part of his life was devoted to great bridge projects in the New York area, and it was fitting that his project should hold the world's record at the time of its construction--977½ feet between steel bearings and 1017 feet between the faces of the abutments.

Modern bridge records do not last very long, however. In 1922 Dr. J.C.C. Bradfield, Chief Engineer of the Public Works Department of New South Wales, took an extended tour to study the chief long spans of the world and returned with the Hell Gate Bridge idea. Dr. Bradfield then drew up general plans and Ralph Freeman, consulting engineer, designed the structure destined to become the heaviest (50,300 tons of steel) and widest

(160 feet) arch bridge in the world--the Sydney Harbor Bridge. Like Lindenthal's structure this became an overhead arch type with a large portion of the roadway suspended from the trussed arch by means of hangers. Although work was begun in 1923 and the bridge did not open until 1932, the actual working period only covered six years, the rest of the time being consumed by labor disputes. The span of 1650 feet which looked good for a world's record at its time of inception was doomed never to be a record at all.

The Bayonne Bridge (1928-1931) shattered that illusion, for it was completed months ahead of the Sydney structure, spanning the Kill Von Kull from Bayonne, New Jersey to Staten Island, New York, with a distance between hinges of 1652 feet. Designed by O.H. Ammann, under the Port of New York Authority, this bridge was the first to make extensive use of carbon manganese steel. Like its two large predecessors the roadway of this bridge is suspended from the arch, whereas in the majority of cases in the less spectacular spans the road runs on top of the arch.

Once more we find the arch important, this time in steel. Its designers have shown that a steel arch can be a thing of beauty as well as of utility and economy. On such a basis its use in the future appears assured.

MODERN CANTILEVERS -- The success of the Firth of Forth Bridge made it appear for a time that the cantilever would be supreme in the long span field. In 1900 designs for the Quebec Bridge over the St. Lawrence were begun by the American engineer, Theodore Cooper. During construction in 1907 a bottom chord buckled

and the whole structure collapsed. It was obvious from the failure that the accepted empirical design rules laid down as the result of previous tests on small scale compression members did not hold for full scale members. Subsequent large scale experiments and studies resulted in a much heavier design on a more scientific basis. The bridge was finally completed in 1917, its span of 1800 feet being the longest of its type in the world.

Other less pretentious cantilevers were erected during and after the Quebec Bridge. Notable among them is the Carquinez Strait Bridge which completed the coastal highway from Canada to Mexico in 1927. Containing two cantilever spans of 1100 feet the total bridge length with approaches is 4482 feet. The suspended span was lifted into place in thirty-five minutes, whereas the suspended span of the Quebec Bridge was lifted the same distance in four days--a notable example of how construction procedures had advanced in ten years.

Worthy of mention is the San Francisco-Oakland Bay Bridge (1933-1936), in reality a series of bridges stretching out for a length of eight and a quarter miles. The main parts of this structure include two suspension bridges, a tunnel, a cantilever, five truss spans, and a series of simple girder spans. Directly responsible for the work were C.H. Purcell, C.E. Andrew, and G.B. Woodruff, who were, of course, advised by a distinguished board of architects and engineers. The cantilever portion of the bridge was itself a huge job, its 1400-foot span being surpassed only by the Firth of Forth and Quebec Bridges. Of particular interest were the dome shaped caissons invented by Dan Moran, which enabled the workers to place the foundations at a record-breaking

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depth of 240 feet. No one can claim great beauty for the cantilever, but its ruggedness and economy under certain conditions make it a type which will endure for some time. It is doubtful, however, that it will ever regain the popularity it held in the early part of the twentieth century when it was widely accepted as the best type for long span construction.

MODERN SUSPENSION BRIDGES -- Successor to the cantilever as the long span type is the modern suspension bridge. It was formerly believed that the suspension bridge could not be made sufficiently rigid to carry heavy concentrated loads, but improvements in stiffening design have changed that belief. Then, too, the lighter load of the automobile which now demanded bridge service became a factor not heretofore considered. The recommended ratio of the stiffening truss depth to the span at the beginning of the century was one-fortieth, a figure which was later decreased to the range of one-fiftieth to one-ninetieth for spans between 2000 and 3000 feet. The ultimate appeared to be passed by the 2800-foot Tacoma Narrows Bridge (1940) at Puget Sound, which had a one-three-hundred-and-fifteith ratio during the four months it stood. Other factors contributed to the bridge's high flexibility which combined with its aerodynamic instability to send the six and a half million dollar structure crashing into the Sound below, the victim of a forty mile an hour wind. But the story of the modern suspension bridge is essentially one of success, of breathtaking achievement and promise of a bright future. In European practice the eye-bar or chain type

of suspension has predominated, although for span lengths over a thousand feet with present metals, chain becomes more expensive than cable. The biggest drawback to chain, however, is the cumbersome methods needed to put it in place. Chain has been used successfully with self-anchored suspensions, where the masonry anchorages are eliminated and the chain is led to a stiffening girder in the floor. The tension in the chain is transmitted to the girder which acts as a strut for the full length of the bridge.

One of the earliest examples of this type was the 605-foot span over the Rhine at Cologne (1915). Pittsburg received three bridges of this type in the latter 1920's, and in 1929 a record span length on the continent was established over the Rhine between Cologne and Muhlheim--a twisted cable span of 1033 feet. Not a self anchored-type is the longest eye-bar suspension in the world, the 1113-foot-9-inch Floreanopolis Bridge (1920-1926) in Brazil. Designed by H.D. Robinson and D.B. Steinman, this structure was the first to use the new structural material, high-tension, heat-treated carbon steel eye-bars. It also made use of rocker towers rather than rigid or flexible towers which were in general use heretofore.

Another feature which has been introduced and developed by Robinson and Steinman is the pre-stressed twisted wire rope cable, as differentiated from the more generally used parallel wire cable. Its designers claim lower cost and shorter erection time for spans up to 1500 feet. Two of their best known bridges erected with this feature have been the 950-foot Grand'Mere Bridge (1929) at Quebec and the 1207-foot St. John's Bridge (1931) at

Portland, Oregon. Most of the design thus far in the United States has been with the parallel wire cable. A hasty examination of the record reveals a startling increase in span lengths in a few years. The first to surpass the Brooklyn Bridge was the Williamsburg Bridge (1903) over the East River, with a main span of 1600 feet, only to be surpassed as follows: 1924 Bear Mountain Bridge, 1632 feet; 1926 Philadelphia-Camden Bridge, 1750 feet; 1929 Ambassador Bridge, Detroit, 1850 feet; 1931 George Washington Bridge, New York, 3500 feet; and 1937 Golden Gate Bridge, San Francisco, 4200 feet. And the end is still not in sight, for spans between 10,000 and 15,000 feet appear to be possible. By way of contrast, the cantilever with present materials appears to have a theoretical span limit somewhere between 5000 and 6000 feet, with a practical limit around 3000.

Each of the above bridges has a story of spirit and courage which would run to many pages, but we shall have to pass on with simply a few comments. Designed by Leffert L. Buck, the Williamsburg Bridge was the first large suspension bridge to have steel towers. It also represented the extreme in stiffening, having a depth to span ratio of one-fortieth, a factor which greatly contributed to its clumsy appearance. The tendency of suspension bridges since then has been toward the more slender and graceful side. Ralph Mojeski's Philadelphia-Camden Bridge over the Delaware River is remembered best as being the first of its type to surpass the Firth of Forth Bridge in span. Built by the Port of New York Authority under the direction of O.H. Ammann, with Cass Gilbert as consulting architect, the George Washington Bridge

over the Hudson at New York City represented a tremendous stride forward. While no longer the greatest span, it can still lay claim to being the heaviest suspension bridge in the world designed for the heaviest loads. It is the only large unstiffened suspension bridge in the world, made possible by the fact that its dead weight is so great compared with the live load it carries.

Of even greater fame is the Golden Gate Bridge at San Francisco. In 1918 a resolution was introduced in the City Council which led to the eventual appointment of Joseph B. Strauss as chief engineer of the project in 1929. Actual construction did not begin until 1933, however. Not only were its bridge piers the first ever built in deep open water, but this is the only structure which was ever built across the outer mouth of an important ocean harbor. A notable contribution in the field of foundations was the introduction of a structure designed as a cofferdam and as a fender to protect the completed pier. Another new procedure was the introduction of a safety net, a device which saved nineteen lives. Some idea of the magnitude of the undertaking may be realized when we consider that with approaches the bridge stretches to 8981 feet, being composed of two end spans of 1125 feet in addition to the main span of 4200 feet. The towers, highest in the world, reach to 746 feet, and the two cables which are more than 3 feet in diameter each contain 61 strands of 27,572 wires.

Despite its gigantic proportions even this magnificent structure will soon be surpassed, for already designs of greater magnitude have left the drawing boards and will soon be in

the process of execution. As typical of the twentieth century as was the semi-circular masonry arch of Roman times, the suspension bridge faces the future with promise of even greater glory and achievement.

Summary

In looking back through history we note that fundamentally bridge forms have remained the same as nature presented them to us, i.e. the arch, girder, cantilever, and suspension. Evolution has come about largely through the adaptation of new materials and construction methods to the forms already established. There is no doubt that the change in the type of traffic has played a great part in hastening that evolution, but use of materials has remained the fundamental force.

We have traced the rise of the masonry arch from the semi-circular masterpieces of the Romans to the elliptical beauties of the late eighteenth century. When iron began to displace stone as a building material, there was a period of retrogression in architectural and structural results, but the entrance of steel in the latter part of the nineteenth century signaled a revival in the arch--a revival which has continued with increasing vigor to the present.

In like manner the beam from earliest times found its best expression in wood. With the rise of the railroads in the early nineteenth century it was natural that some type of bracing should appear to take the increased loads, and thus the truss appeared. Iron and then steel expanded the use of the truss

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until now it finds itself in most structures, a vital part of the stiffening system.

The cantilever, though used sparingly throughout the ages in wood and stone, came into its own with the age of steel in the latter half of the nineteenth century. It also enjoyed great popularity in the long span field in the early twentieth century, but appears at last to have been out-distanced by the suspension bridge.

While suspension bridges have also existed since earliest times, they are really a product of the wrought-iron and steel age. With automobile traffic of the twentieth century demanding longer and longer spans the suspension bridge has come into its own, at least for the present. New materials may render some other type dominant, but prophecy in that direction is difficult. Aluminum is beginning to appear and metallurgists are constantly improving other structural metals. It is too early yet to say what form reinforced concrete will assume in the bridge of the future.

At any rate, progress will come largely as the result of the discovery of new materials and of new ways of handling old materials. The future lies with the bridge engineer--in his hands the bridge will reflect, as it has in the past, the true progress of our civilization.

19. Serfland, op. cit., p. 7.

20. Heintzeling, The Bridge of America, p. 120.

21. McCullough & Thayer, op. cit., p. 120.

22. Burr, U.S., & Falk, N.S., op. cit., p. 120.

23. Steinman & Watson, op. cit., p. 120.

FOOTNOTES

1. Smiles, S., "Lives of the Engineers," (Smeaton & Rennie),
pg. 52-53.
2. Steinman, D.B. & Watson, S.R., "Bridges and Their Builders."
pg. 28.
3. Brangwyn, F. & Sparrow, W.S., "A Book of Bridges." pg. 145.
4. Admiral Don Antonio de Ulloa, "A Voyage to South America,"
(Madrid: 1748).
5. Steinman & Watson, op. cit., pg. 21.
6. Waddell, J.A.L., "Bridge Engineering." chap. I.
7. Herodotus, book I, chap. 186.
8. McCullough, C.B. & Thayer, E.S., "Elastic Arch Bridges." pg. 5.
9. Plutarch's Lives, transl. by J. & W. Langehorne, vol. I,
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13. Encyclopoedia Britannica, 11th ed., "Bridges."
14. Cresy, E., "Encyclopoedia of Civil Engineering." pg. 415.
15. Encyclopoedia Britannica, 11th ed., "Bridges."
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17. Steinman & Watson, op. cit., pg. 90.
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19. Merriman, M. & Jacoby, H.S., "Roofs & Bridges." pg. 7.
20. Heinzerling, "The Bridges in Eisen." (Leipzig: 1870)
21. McCullough & Thayer, op.cit., pg. 12.
22. Burr, W.H., & Falk, M.S., "Metallic Bridges." pg. 27.
23. Steinman & Watson, op. cit., pg. 168.

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