ESSAY

ON

THE THEORY AND HISTORY

OF

COHESIVE CONSTRUCTION,

APPLIED ESPECIALLY TO THE TIMBREL VAULT.

READ BEFORE THE SOCIETY OF ARTS,
MASSACHUSETTS INSTITUTE OF TECHNOLOGY,
BOSTON,

BY

R. GUASTAVINO, ARCHITECT.

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Che tu sia un appassionato
o uno studente di Architettura,
fidati di questo vecchio testo,
trasformane il sapere portandolo ai giorni nostri.

E quando ti capiterà di applicarlo,
ricordati di chi lo tramanda.

Antiche Fornaci Giorgi
COTTO FATTO A MANO - DAL 1735 A FERENTINO

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DEDICATED

TO THE

SOCIETY OF ARTS,

MASSACHUSETTS INSTITUTE OF TECHNOLOGY,

BOSTON.

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PREFACE.

In October, 1889, at the request of the eminent and well-known architect, Mr. T. M. Clark, the Honorable Society of Arts of Boston paid me the distinguished compliment of inviting me to describe what observation and experience had taught me in regard to the system of arches which at that time I was constructing in the new Public Library of that city, in Copley Square.

My easiest plan, and the one which I should have followed, perhaps, to avoid the charge of pretentiousness, would have been to simply explain the practical work which comes in my line of business, and not tread on slippery ground by any analysis and theory. But two reasons obliged me to overlook this, and to enter into theory also.

The first, and most important reason was, that to build an arch on this system, or build anything on the Cohesive System, presents two problems. One relates to the stability of the structure after being built; the other, and the main one, to getting the structure built. We may know that a construction on the "Cohesive System" will have stability when set; but to build it may be an insuperable problem.

It is not only to build a wall or arch over a solid centre, where one brick is set over another brick, one stone over another stone, and where, any defect being found, it is a simple thing to correct or change it. For a structure, generally in open space, acting always in inclined or horizontal pressure and thrusts — a structure where the main strength will depend on the cohesion, and which, at the moment of construction, has not this cohesion — presents a serious problem. Consequently it was necessary for me to study the problem carefully. This was not so easy, especially when academies and books could teach but little, if anything, on this subject.

The second reason was, that I remembered that, before my fifteen years of practice as an architect, I passed several years at the students' bench in the institutes, universities and academies, and my eminent professors would have the right to see whether I had left dust in my books and notes; and I reflected also that one cannot explain practical things, or have convictions, without some reasons, and those reasons formed the scientific theory which I was obliged to construct in order to have convictions, and also some guaranty that my employés could work safely. Scientific tools were, therefore, necessary, and it was also necessary to have courage to confront the difficult situation, and endeavor to explain, in my limited way, the theoretical part. Perhaps these tools are rough, as is usually the case with new things, yet the perfecting of them is the specialty of the professors, to whom I refer this essay for its completion. . . . But whatever knowledge I may possess on this subject is due, not so much to my researches and investigations, as to the wisdom of my distinguished professors at the Academy of Barcelona, D. Juan Torras and D. Elias Rogent, who instructed and interested me in the study of the arts and applied sciences, calling special attention to this system of construction in embryo, for which I treasure their memory with gratitude.

Finally, the disinterested assistance which I have received from the most distinguished architects, due principally to their ready comprehension of the fact that the new construction is the renaissance of an old and noble system, for several centuries unused, but applied now owing to the necessities of the age, has encouraged me to publish in book form the lectures referred to, in the hope that it will have the approval of all interested in the constructive arts.

R. G.

PART I.

INTRODUCTION.

IN Barcelona, there is a family called Muntadas, who are considered genuine representatives of the aristocracy of the manufacturers of Catalonia. All the members of this family are, or have been, manufacturers, and, together, in the towns of Barcelona, St. Martin, Sans, Gerona and Ripoll, they employ more than ten thousand people in their bleacheries, manufactories, dyeing and printing buildings. One member of this family owns, in the department of Zaragoza, a rich and extensive property that for centuries was possessed by the monks, and is called "Monasterio de Piedra" (the Stone Monastery). This land contains about 50,000 acres, and the buildings thereon, consisting of churches, convents and the palace of the abbot, of different epochs of Romanesque, Byzantine, Renaissance and modern architecture, cover about 200,000 square feet of ground. The owner, Don Frederico Muntadas (who is a great littérateur and pisciculturist), lives there with his family a large part of the year. I was invited by this gentleman, through his uncles Don Jose and Don Ignacio Muntadas, to visit this property, as they intended to convert the immense convent into a summer resort.

It was in October, 1871, when I made my acquaintance with this estate, which is four miles from the railroad station of Alhama, Aragon, a noted hot-spring resort.

Here, in that "Monasterio de Piedra," I saw a grotto of immense grandeur, one of the most sublime and extraordinary works of nature. Imagine Trinity Church, Boston, covered by an immense natural vault, supported by walls of the same nature, with gigantic stalactites of all kinds of forms and dimensions, like great chandeliers, hanging from above; the floor a lake, receiving the whole light through an immense ventinel or opening, like a rosette window in a cathedral, covered by the fall of the full mass of water of the river Jalon, its builder, passes over the vault and precipitated more than two hundred feet, taking the form in its fall of a horse's tail, which is the source of its name, "Cola de Caballo."

I had just left Barcelona, after completing some buildings, among them the large manufactories of Batllo Brothers, and was under the impression that I had accomplished something, in these buildings, according to the Cohesive System ; but with this great specimen of nature's architecture before me, I recognized how small and insignificant my work had been.

The thought entered my mind, while in this immense room, viewing this fall of water, that all this colossal space was covered by a single piece, forming a solid mass of walls, foundation and roof, and was constructed with no centres or scaffolding, and especially, without the necessity of carrying pieces of heavy stone, and heavy girders or heavy centres ; all being made of particles set one over the other, as nature had laid them. From that time I became convinced that there was much to learn from the immense book called Nature, never enough studied, and that our ordinary system of construction was very poor, notwithstanding that we possessed the material for this kind of building that enabled us to imitate nature. Hence I understood why my distinguished professor of construction, D. Juan Torras, said one day : "The architect of the future will construct by imitating nature, because it is the most rational, durable and economical method." This grotto is really a colossal specimen of cohesive construction. Why had we not built on this system ?

I knew that in the south of Europe, and in Asia, there existed many buildings on the Cohesive System, erected centuries ago. The types are some of the Roman triumphal arches, the Pantheon, the cupola of the Santa Sophia, the cupola of the Cathedral of Zamora, and others in Asia, and some in Moorish constructions of the Middle Ages. The larger part of these constructions are of concrete; that is, some are built with marble facing or other stone outside and concrete on the interior, while others are concrete throughout. The first attempts made in my enthusiasm for the Cohesive System were carried out in simple concrete. But I soon found that no arch work could be done with concrete — that is, cement combined with broken stone, gravel or sand, to satisfy the needs of the epoch — so well as it could be accomplished with tiles. By this I mean tiles laid in cement, if the material and process are well adjusted. In consequence of this experience the factories of Batllo were projected for tile arches and not for concrete (1869 and 1870). The question, therefore, arose in my mind, which would be the better system — that of the Cohesive Construction based on concrete material, or the tile system, like that used in the floors and ceilings of the Batllo buildings?

Such concreting, in truth, is the imitation of the conglomerates of nature, but, as in nature, requiring great mass and, as a principal factor, TIME, in order to have strength. This process, however, I found too heavy and too slow for this epoch, in which, of course, we appreciate the value of time. But the tile system, on the other hand, was not the desirable one, on account of the excess of plaster required; besides, there was the irregularity of the Portland cement of the market to contend with. These two difficulties were more than an obstacle, they were an imperfection.

Under these impressions and conditions I commenced work in Barcelona, beginning with my own private residence, on the corner of Aragon and Lauria Streets. I tried the first experiment on myself, as a physician might try his own medicine, carrying out my ideas by building a construction four stories in height, practically with no beams, using clay and cement. Afterwards I built the bleacheries of Muntadas Aparicio & Co.; a merino and other woolen-goods factory for Carreras & Sons; another, also a merino factory, in Villa Franca, for Michans & Co.; the glass manufactory of Modesto Cossademunt; the Theatre of Vilsar; the manufactory of porcelain for Florens & Co.;

and the silk manufactory of Saladriguez. I also made some applications of the system in the private houses of the bankers, D. Victor Blajot and D. A. Anglada, and others.

But all this work was almost empirical. It had not the right technical sanction, and how was it possible to have it? The thickness of the arches was determined by intuition and practice, as a competent blacksmith determines the size of the pieces which he uses, or a competent sailor the size of a rope or block. But can he satisfy the sciences with these? Can we have any guarantee by these alone? On the other hand, was it possible to determine anything in the embryo state of the manufacture of cements fifteen or twenty years ago, when no manufacturer was able to guarantee his own brand, because of the difficulty in obtaining regularity in it; when each manufacturer had his own formula, and when, in consequence, the market could not be supplied with a sufficient quantity of each brand to make an average test of strength upon which to base any calculations; and where there was no certainty of always being able to procure in any market the quality of cement upon which our coefficient was based?

That was the condition of affairs in Spain, and in fact, all Europe, fifteen or twenty years ago, and that is still the condition in several countries. Fortunately, the plans of the buildings and factories referred to were sent to the Philadelphia Centennial, in 1876. The success attained there, and the great Chicago fire, which made an impression on all European minds, convinced me that this country was the proper place for the development of the Cohesive System. But I did not succeed in coming here until 1881.

I had not been here long before I recognized the necessity of studying American methods, materials and facilities. To this work I devoted five years. It was absolutely essential that I should be well posted, particularly in the matter of the timbrel arches: First, because cement is the essential part; second, because of the position of the arches, as failure on their part must endanger the lives of workmen; third, because the application of the arches being for floors, and requiring speedy work, required also that the floors should in a short time be delivered over for use, and in consequence it was necessary for me to know exactly with what kind of material I was going to work, and under what conditions.*

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*Yet, at the present time, notwithstanding the progress in the manufacture of Portland Cement and the great stock in the market, we must use every precaution as to the quality of the cement we are using.

Explanations were given to interest prominent architects and builders. But some seemed to take the matter as a dream, or as though I were a visionary; while others, more benevolent, said it might be beneficial in Spain or Italy, but never in this country, so different in climate, processes and necessities.*

On the other hand, the manufacture of tile here was almost an impossibility; because, if it was accomplished by hand-work it would be very dear, and if by machinery, the probabilities were that it would come out too heavy and useless. Consequently the obstacles and difficulties seemed insuperable, and hope almost left me.

Fortunately, work and perseverance are two great factors towards success.

The publication of some artistic works in illustrated papers were received with appreciation, and some successful competitions for semi-public buildings in New York put me in posi-

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* NOTE. — Surely the latter were not aware that in Spain 95 per cent. of the architects and 99 per cent. of the builders did not know or may not have heard anything about the system, that the same was apparently true in Italy, and that the fire-proof floors general in both these countries in important buildings were in use long before the flat hollow brick arches and iron beams also used here, tile arches only being used in some states in small arches for common and cheap constructions.

tion to begin, with some authority, a series of tests and experiments with imported tiles.

After ending my connections with my clients, my first work done with this fireproof system in America, was in a four-story private house on 78th Street, New York, in 1886, with American tiles. During the same year I commenced to build the interior of the Arion Club, 59th Street, whose building committee accepted my proposition when they ascertained that with my arches they could make a saving of over $5,000, in two floors alone, over the ordinary system of fireproofing.

From that time on I have been building in New York, having erected floor arches in several different structures, among them being the residence of W. Fellows, Esq., in Montclair; the Corbin Building, corner of John Street and Broadway; the Edison Electric Illuminating Company's Station, 26th and 29th Street, New York, etc.

Because of these encouraging results, indicated in the number of applications for contracts, in July, 1889, I put all my affairs in the hands of a corporation, calling itself the Guastavino Fireproof Construction Company. But, if the system has become popular, it does not owe its popularity to its name, but to its adjustability and its own merits. I have now the satisfaction of seeing a system of construction established on a good and satisfactory basis, which only four years ago was considered a dream, and which two years afterwards was noticed in a prominent technical book as a simple curiosity only. It is a great satisfaction to me to be able to say that all the great obstacles which confronted me in my work have at last been overcome.

PART II.

RESEARCHES AND HISTORY.

(1) THE "Timbrel Arch" is not entirely new. It is as ancient as the "Cohesive System," and may be as old as its opposite, which may be called the "Gravity System." But although the "Cohesive System," including the application of timbrel arches, was frequently practised by the ancients, after reaching the height of its splendor in the Middle Ages it gradually disappeared, in proportion as modern civilization and the Renaissance approached.

(2) Was its disappearance due to the fact that after this great constructive age the architects were not builders? Or was the disappearance of this form of construction in Europe caused by the decadence of the influence of Oriental Architecture, after the great classic era of the Arabs, or rather the Moorish-Spanish Architects, who knew how to decorate construction and to construct decoration in the "Cohesive System," as did the Greeks, centuries

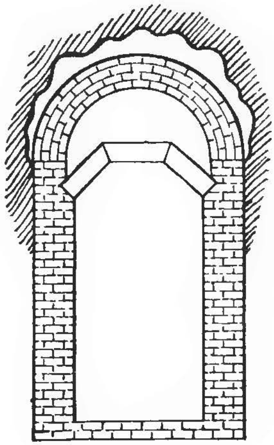
before, and the Græco-Romans, in their style? This is exemplified in their system of construction by gravity.

(3) We have no definite knowledge on these points, but without the mighty fact of the existence of some monuments in the "Cohesive System," which testify to epochs of undoubted progress in constructive art, it would be impossible to realize or believe in them.

Much has been said of late against vaults, and especially "Timbrel Arches"; in the first place, against their utility and application, and secondly, regarding their origin and ancient use. The most erroneous and contradictory ideas have been emitted in regard to this vaulting, as before occurred with the arch itself, the latter having been credited to the Romans.

(4) To-day, all that are known are studied by exact designs from a great number of antique monuments, some extant and others in ruins; and we can from these draw the truth and infer history. We can thus say that the general use of vaults of brick, stone or the timbrel, as well as the use of the arch itself, and its origin, is very ancient. They were applied before the days of the Romans, who did nothing but improve, making their use general, and giving to them more or less an æsthetic character, which

had not been done before; because the arch and the vault had hitherto been used solely as a constructive necessity where blocks large enough to cover the space could not be procured. For this reason the arch in the "Gravity System" appeared, as well as the "Timbrel Arch" in the "Cohesive Construction."



No. 1.

EGYPT.

(5) In a tomb situated in the vicinity of the city known by the name of the City of Sepulchres, near Thebes, there is an elliptical vault constructed of unburned brick. It is 2.50 m.

in length, by 1.42 m. in height, measured from the springing. Among the hieroglyphics which adorn this monument the name of Amenophis can be discerned. It must thus belong to the time of the eighteenth dynasty, dating some seventeen centuries before our era. This is in regard to the brick vault in general. Another specimen in regard to the "Timbrel Vault" —

(6) In one of the Pyramids of Egypt, at Gizeh, a tomb discovered by Colonel Campbell (see Fig. No. 1) forms an arch of unburned bricks. These bricks measure 0.170 m. by 0.126 m. by 0.50 m. In order to give them the necessary curve it is understood that they had to be curved before being dried. The construction plainly shows that the flat brick was used with the idea of decreasing the number of pieces, closing the space with the least possible joints. Thus, to give more strength and cohesion to the arch, they are applied in four rows, one above the other, breaking the joints, constituting through this medium an arch without joints. (See "General History of Architecture," by D. Daniels.)

(7) It is seen by this specimen that the cohesive form, as well as the typical timbrel arch, and the arch in general, was, so to speak, "born," and is not any particular invention. Nor did

it originate by any determinate civilization. It was simply the fruit of necessity, a spontaneous resource of the most ancient times.

(8) This plainly shows that neither brick vaults, stone vaults nor timbrel vaults can be said to belong to any civilization. Similar circumstances necessitated their creation in every country.

ASSYRIA.

(9) The Assyrians improved the manufacture of brick. Encamped between the rivers Tigris and Euphrates, and with abundance of clay at their disposal, as well as asphalts and mineral oils, which they used as fuel, they came to the practical idea of burning the clay, and instead of using raw brick, they used burnt. For such purposes ovens were needed; hence the necessity for covering and closing space without lumber or stone, but with bricks and terra-cotta. Thus were the dome and cone shapes developed that they were using in their ovens.

(10) The ovens for the manufacture of brick were large domes constructed with bricks or tiles of large dimensions. In some of their experiments the bricks were laid flat, advancing one over the other (Fig. 2), each layer pro-

jecting about an inch, and in this manner forming a curve. (See "General History of Architecture," by D. Daniels, already mentioned.)

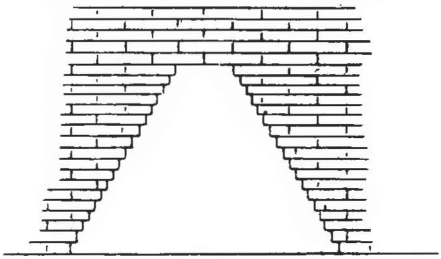


Fig. 2.

(11) The Assyrians attached great importance to the surface of their bricks, possibly to give them conditions of cohesive strength. For instance, the dimensions of the bricks used in the library of the palace of Khorsabad, and in the palace of Nimrod, were 35 by 32 by 7 centimetres, or about 14 by 12 by 2 inches.

The gardens of Semiramis, at Babylon, and the subterranean passages under the Euphrates, were nothing else but vaults built with very large bricks.

GREECE AND ROME.

(12) The Greeks and Romans did not use the brick in a better manner than the Assyrians.

Their facilities for obtaining clay and fuel were not favorable, and they were therefore more devoted to stone construction. The Romans, in particular, had a marked predilection for stone and concrete, of which they made very good use, not only in triumphal arches and bridges, but also in military and urban constructions, such as sewers, etc. This is illustrated by the sewers which they left in Valencia, Spain, similar to those in Rome, although clay was plentiful in that country. [Through these sewers of Valencia a wagon can easily pass.] The aqueduct of Segovia and the city walls of Tarragona are other specimens, again showing their predilection for stone and concrete. The former is a wonderfully magnificent structure and a model of static equilibrium.

(13) We may remark that when the Romans used brick it was generally as a small voussoir, as may be seen in the Flavian amphitheatre, or the Coliseum; not only in the primitive works in this building, but when rebuilt at different periods, they were used as voussoirs in plain brick arches.

(14) The only specimens which seem to have existed as vault work, or timbrel, of brick placed flat in imitation of the specimen shown on page 23 (No. 1, Egyptian), are some that

were probably in the baths of Antonius Caracalla. The architect found difficulty in furnishing light to the central part, which could only receive it through penetrations in the vault. But for this purpose it was necessary to weaken the arches, and if they were constructed of brick, like those of the Coliseum and others, they had to be given a great thickness and required walls of immense resistance. It seems that the result desired was at last obtained by constructing the vaults with bricks on end, or a timbrel arch, using, I suppose, puzzolana (Pozzuoli) cements, which were slow setting but good, and using, may be, centres which supported the vaults until after the mortar had settled. But of this we cannot be sure, as may be inferred from the following paragraph, taken from the treatise on "Vaults and Bridges," by Samuel Ware.

(15) "The recollection of the Solar Bath of Antonius Caracalla in the present age, when we assume to ourselves so much credit for the invention of iron bridges, may serve to abate some of our enthusiasm. It was a circular building 111 feet in diameter, the roof a dome, composed of *copper and brass.*"

(16) Spartian says of it: "Reliquit thermas nominis sui eximias quarum cellam solearem

archtecti negant posse ulla imitatione qua facta est fieri, namex aere vel cupro, cancelli superpositi esse dicuntur, quibus concameratio tota concredita est; et tantum est spatii ut idipsum fieri negent potuisse docti mechanici."

(17) By the foregoing it would appear that "cancelli" were *ribs* and the "concameratio" *plates* similar to what may be seen in our iron bridges. From this historic description cited by Samuel Ware, it follows that, if the small domes and arches were constructed with "Timbrel Arches," the large dome was certainly not built in the same way.

THE MIDDLE AGES.

(18) The true epoch of the development of the "Cohesive System" and the dome was in the Middle Ages, but no important specimens of the "Timbrel Vault," or with the brick set flat against the centre, are left. We must, however, for several reasons, call attention to the construction of arches and domes in the Arabian epoch, and that of the Mussulman in Persia, a country where a new and powerful civilization was already developed, on the spot where the Assyrian left the trail of his ceramic work — a civilization that is dying out under the vast cupola of St. Sophia.

(19) The cupola was the dominant line of their monuments (see Coste, Architect, 1840 and 1841, "Voyages en Perse"); and as the Oriental civilization had great influence in the antique Byzantium, not only did it give to the Byzantines the richness of their colors and decorations, but it gave also the foundation for new ideas in the architectural arts; to such an extent, that it founded the classical examples of the "Cohesive System."

(20) The greatest development was in Cordova and Granada, Spain; but under the influence of the beginning of this civilization the construction of St. Sophia, the grandest and most finished model of the cohesive cupola, was carried out. The cupolas of Persia are all constructed over brick walls, and are the continuation of the same wall with the same material.

(21) From the building of the cupola of St. Sophia to the period of the Renaissance several cupolas on the cohesive principle were constructed. The principal of these cupolas were the Mosques of Solyman II., Sultan Ahmet, and the Holy Apostles, of Constantinople; Santa Maria of Ravenna; St. Mark, Venice, and the Cathedral of Zamora, whose cupola is one of the most beautiful in Europe.

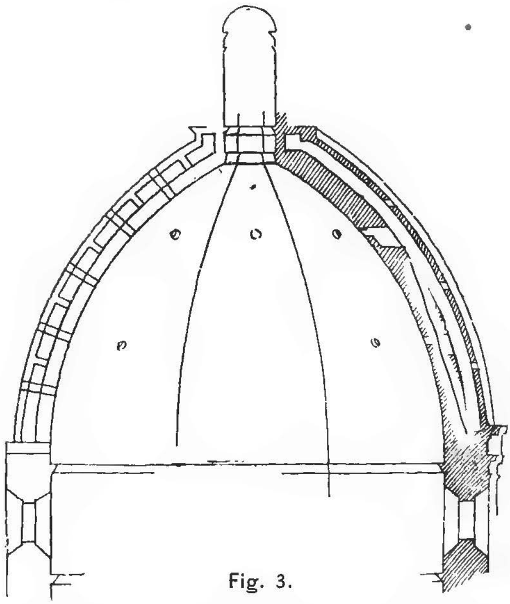


Fig. 3.

(22) After this epoch, in the Renaissance, the most remarkable are those in the Santa Maria del Fiore, and the Medici Chapel and Baptistry of Florence; St. Augustine's and St. Peter's in the Vatican, Rome; the Madonna de la Salute, Venice; Ste. Geneviève, Paris; St. Paul's, London; La Real capilla de los Desemparados, Valencia (Fig. 8) and the Dome de los Escolapios (Fig. 9), Spain.

(23) It may here be appropriate to call attention to one important point. All the cupolas constructed, up to the epoch of Constantine,

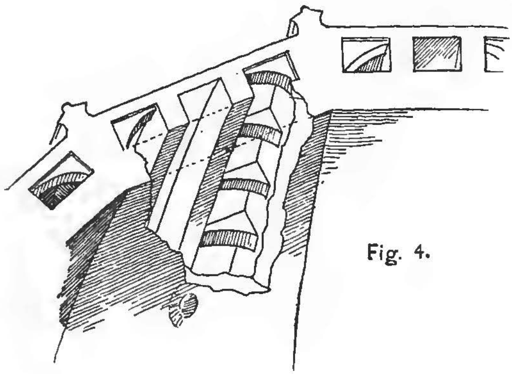


Fig. 4.

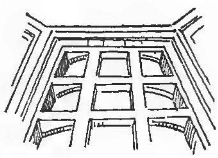


Fig. 5.

were with brick and concrete, in the Arabic style, following the constructive lines without altering the æsthetic forms; and in all the cupolas built after the time of Constantine, beginning

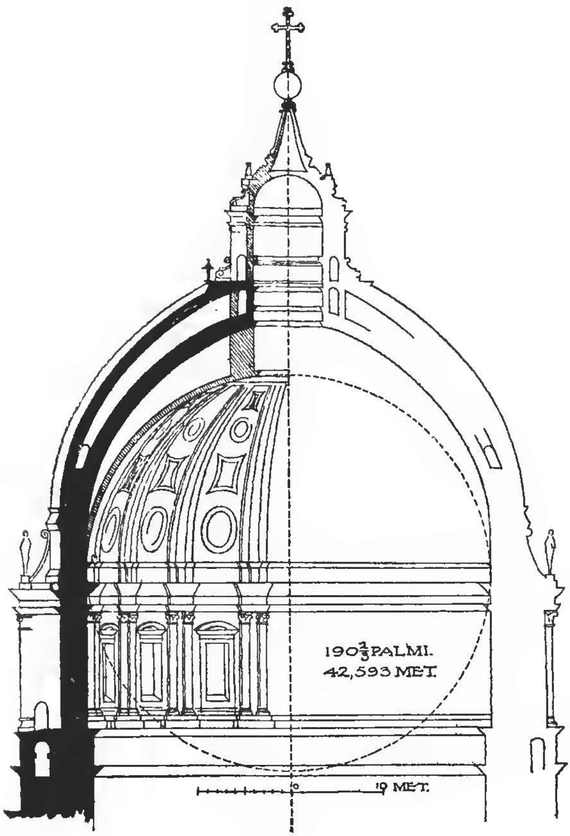


Fig. 6

with the period of Brunelleschi in Florence, including the dome of St. Paul's, London, the exteriors are not the representation of the interiors, being successively more prominent. This deviation, in the modern ones, can be seen by comparing the Brunelleschi cupola with St. Peter's of the Vatican and St. Paul's of London (Figs. 3, 6 and 7). Brunelleschi's double cupola, outside, is adapted to the same shape as the inside, giving, apparently, only the hollow space, perhaps to give dry conditions for later decoration, as can be seen by the details of the ribs (Figs. 4 and 5). In the last cupola mentioned (Fig. 7), the interior dome or decoration is a hemisphere, the second one is the same shape as a truncated cone, and the third one is the exterior dome. The whole does not represent the progress of the art of instruction and the way to apply æsthetic forms.

(24) This anomaly is due to the fact of the disuse of the hydraulic mortars of the Romans, Arabians and Byzantines, because the art of manufacturing these materials, which constituted the basis of their cohesive construction, was lost. In the construction of St. Sophia the Byzantines used baked clay and lava of Vesuvius, or pumice-stone.

RENAISSANCE.

(25) The architects of the Renaissance, especially in Italy and Spain, were greatly impressed by the works of the Romans, Byzantines and Arabians, and wished to imitate their bold

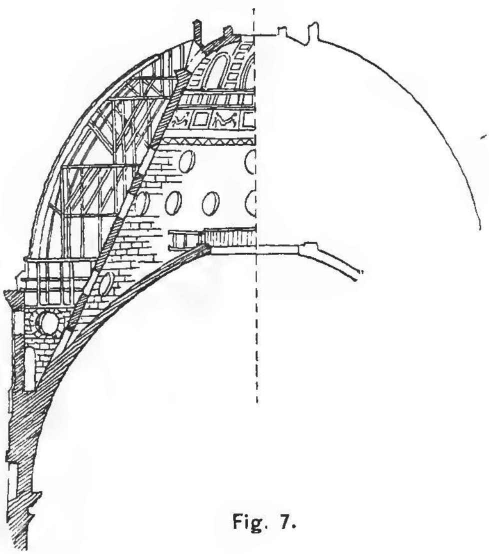


Fig. 7.

construction; but they did not have at hand either the material or the skilled hands. They therefore used plaster, and thenceforth the timbrel arch was introduced along the coasts of the Mediterranean from Murcia to Valencia, Barcelona and Genoa, and along the Italian coast to Naples. Remains of the timbrel arch will be found in all those parts. This epoch demands great attention because of the many facts it supplies to aid us in our study.

(26) When the architects of the Pontificate, in order to supply the richness and grandeur called for in this epoch, took for their models the Roman and Byzantine construction, as already stated, they had neither the material nor the skilled labor necessary; consequently it was impossible for them to imitate when they had only common air-lime and plaster. The first they found impossible to use in constructions similar to St. Sophia, the Cathedral of Zamora or the Arabian cupolas. As to the second, they found that the unlimited expansion of the plaster, which only stops when fully saturated, —that is, when it loses its power of absorption, —compelled the architects to supply walls of enormous thickness. Besides this disadvantage, when the plaster has arrived at this condition of saturation its strength is gone, loosening the bricks principally where the building is exposed to the weather or subject to alternate changes of humidity and dryness. In consequence, its use was limited to very heavy walls,

and for ceilings having wooden beams and wooden boards, over which were laid Arabian tiles if it was a roof, and mortar and flooring tiles if it was a floor.

In some cases the timbrel vaults were used as a ceiling and floor, having two or three thicknesses of tiles with plaster, and the haunches were filled with light pottery ; this pottery was leveled over with rubbish and mortar, finishing with flooring tiles.

(27) It is necessary to remark that all of this construction was used only in large buildings, such as convents, palaces and churches, where the walls were very thick, amounting to one-third of the full span, and where the character of the building was a guarantee that the ceilings would not be abused; otherwise it was necessary to patch and repair every few years. But in general building it was only used in small spans, such as eighteen to twenty inches between beams, three tiles being used to two courses of bricks set flat over the centre; and in this state it has remained until the present date.

(28) With this I conclude the review of this form of construction, the antique and Renaissance, passing to the modern epoch.

As we may observe, all the timbrel arches of the Renaissance epoch existing in Italy, as

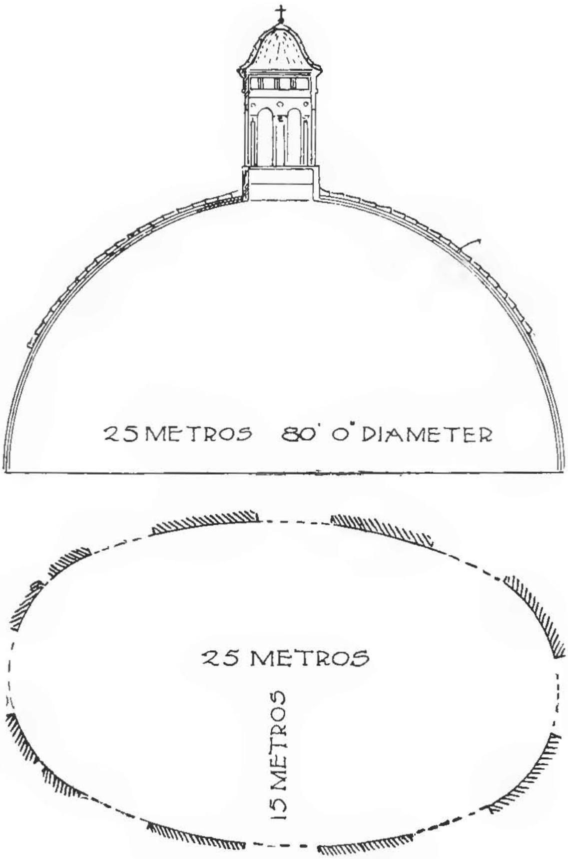


Fig. 8. Dome and Plan.

well as in Spain, are constructed with plaster material, which does not meet the exigencies of good construction. Consequently, it is natural that no technical academy in Spain or Italy has

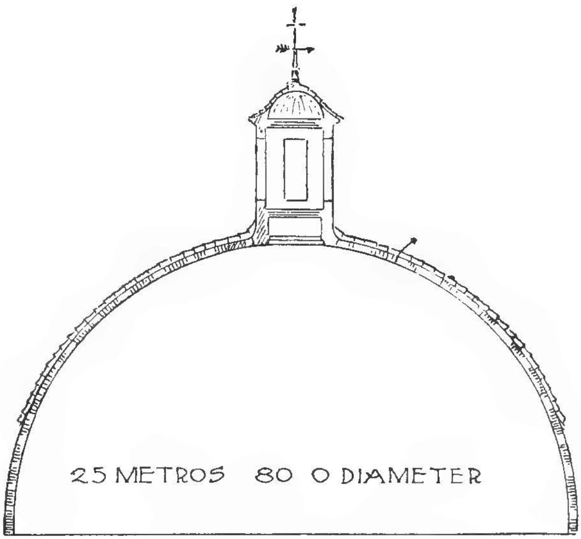


Fig. 9. Brick Dome with Iron Rings.

taken into serious consideration such empiric construction, which has a tendency to lamentable accidents. France and England are not here taken into consideration, because, like the other nations of the north, they have not bricks of dimensions and conditions suitable for the cohesive form; they have bricks of a small top and bottom surface, that is, four by eight inches,

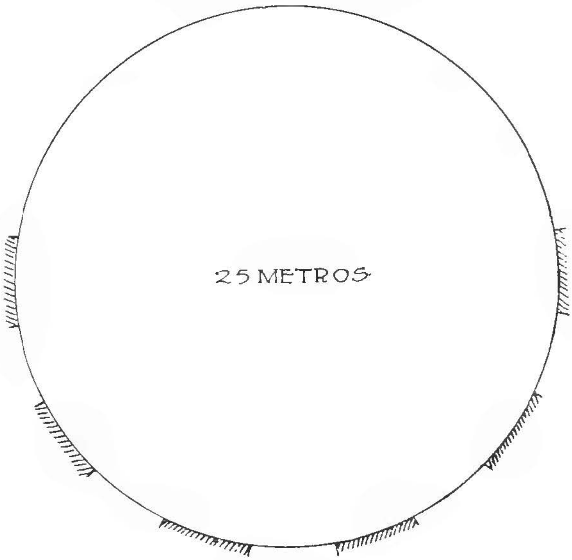


Fig. 9.

when, generally, the types for the cohesive system are the Assyrian bricks, or the bricks of the Orientals, the dimensions of which were about twelve to fourteen inches long, six to eight inches wide and one to two inches thick.

(29) In Spain, where this system has been used and is still in use on a larger scale than in any other country, there does not exist any treatise, or a single work, on the theory of this construction, or a single scientific explanation of this manner of building; not even an empirical explanation to satisfy the curious.

(30) The time that cements began to be generally used in modern days was from 1845 to 1850, and from this date commenced the renaissance of the "Cohesive Construction." The modern Roman cement that Mr. Parker invented and patented in 1791 and 1796 was so dear, and the conditions of setting were so slow, that its introduction into buildings was much retarded.

This cement, in the beginning, was called Parker's cement; its author called it Roman mortar. The other cements called Medina, introduced shortly after, had the same defects. Mr. Aspdin, on the 21st of October, 1824, took out a patent for the formula of the celebrated Portland cement.

This cement was given the name of Portland by the author, Mr. Aspdin, because, when it is good, and smoothed with the trowel, it is very similar to Portland stone when it is polished.

(31) Up to the year 1868 the professors of the academy of Barcelona, one of the most

illustrious of Europe, and a city where tiles are more in use than in the rest of the world, did not commence to pay any attention to this style of construction until important applications had been made of it. And when at last they did, it was only to comment incidentally on its resistance, and its possible utility; but they did not make a study of it, notwithstanding the fact that they were constantly walking over floors constructed on this system in which plaster was used; on the other hand, this want of attention is explained by the lack of cements proper in those days for such kind of construction. The want of proper cements, and of an invariable brand on which to base their calculations, was one of the main obstacles which beset the Catalonian and Valencian architects.

(32) The first work of importance of this character constructed in Spain was in 1868 — the manufactory of Batllo in La Corts de Serria. It is a series of buildings where there are 2,000 people employed with 1,000 looms and 64,000 spindles. Afterwards I built others already mentioned. In some cases the risk and danger caused by the irregularity of the materials was so plain that the workmen were afraid to go ahead, compelling me to remain in the works to inspire confidence and success.

(33) The progress verified in Spain, particularly in Barcelona, in this special construction, was due principally to the manufacturers, and to the studies and teachings of the professors on these subjects, who were debating for several years, at the same time, how to improve their respective specialties, and how to obtain new practical systems of construction, knowing, as they did, that the improvement in material required change and progress in construction. But their noble aspirations were restricted, as they had no facilities; besides which it was necessary for them to content themselves by recommending the theories of Vicat about the use of cements, and other applications well based.

(34) Nothing was done about investigating these structures to which I have referred, and no coefficients were discovered. These only can be obtained when we can depend upon the materials with mathematical regularity, and with powerful apparatus for determining their reliability. They can only be obtained, too, in countries where we can find in the market enough guaranteed brands of Portland cement of different setting degrees; where clay can be used for these constructions with advantage, and with regularity of manufacture thereafter; and, finally, after trial in a country where we have

powerful apparatus, and where coefficients can be obtained, as has been exemplified by our own work for the past five years.

(35) On account of these special advantages it seems that all this experimental work culminated in the United States, taking a natural stand in New York and Boston, with specimens that have no rivals in any part of the world for lightness and resistance. We now see that the movement initiated in England by the unappreciated Mr. Parker, with 1791 and 1796 patents — who thought he had discovered the old Roman cements, — after passing the patented improvements of Mr. Aspdin, of October 21, 1824, may have culminated in New York and Boston. But not without the valuable assistance and confidence of the eminent architects, Messrs. McKim, Mead & White, Buchman & Deisler, R. H. Robertson, F. H. Kimball, T. M. Clark, De Lemos & Cordes, A. H. Pickering, A. F. D'Oench, and others, whose co-operation and support in the annals of constructive art deserve to be held in remembrance.

PART III.

THEORY AND COEFFICIENTS OF APPLICATION.

WE will divide construction in general into two classes:

(36) First, "Mechanical Construction," or, construction by gravity.

Second, "Cohesive Construction," or, construction by assimilation.

(37) The first is founded in the resistance of any solid to the action of gravity when opposed by another solid. From these conjuctive forces, more or less opposed to one another, results the equilibrium of the total mass, without taking into consideration the cohesive power of the material set between the solids.

(38) The second has for a basis the properties of cohesion and assimilation of several materials; which, by a transformation more or less rapid, resemble Nature's work in making conglomerates.

(39) We can give another definition more precise and comprehensive for both systems, in

saying, that the first, or mechanical, system is that where all the pieces can be separated one by one and then rebuilt in the same or similar manner. To this class belong the pyramids of Egypt and the Greek temples, etc. In "Cohesive Construction," on the contrary, the components cannot be separated without destroying the integral mass. To these belong the Babylonian walls of brick with hydraulic mortar; the vaults and cupolas of the Assyrian, Persian, Arabian, Roman and Byzantine—the antique and Middle Age conglomerate construction.

The structures built by the "Gravity System" can at any time be taken down in the pieces out of which they were formed. Thus, the stone or brick that yesterday formed part of a temple or monument dedicated to the memory of a hero can to-morrow belong to or form a part of the walls of a stable; while, on the other hand, though man cannot again use the parts of "Cohesive Construction" for modern buildings, their ruins inspire respect and veneration; and only Nature, with her slow but sure work of disintegration, can take from this style of building its material for her immense and eternal laboratory.

(40) The materials employed in construction by gravity only require the physical quality of

hardness. For the "Cohesive Construction" the materials must not only have proper physical conditions, but it is absolutely necessary that the chemical properties of the substances employed should be taken into consideration. The use of the "Cohesive System" was rendered impossible to many nations because they had neither the material, nor the knowledge of its use, at their disposal; while on the other hand, all civilizations and all nations could make use of the gravity system.

(41) The basis of these materials is mortar that does not require exposure to the air for its transformation or setting quality — that is, hydraulic lime and cement; but for our specialty we must have cements of the quality of Portland. The formula for the manufacture of these kinds of materials, and the manner of their use was, it seems, lost (probably soon after the fall of the Roman Empire), barring some rude practices in the Orient, which soon disappeared, to be found again in 1791 by Mr. Parker. The two patents taken out by him in 1791 and 1796 were not complete, and they came too late to be taken into consideration in the scientific movement, already well advanced, that was giving impulse to the academic and technical schools in the last century, whose text-books in

general did not refer to any save the gravity system. These doctrines or ideas prevail yet, and are now the basis of our teachings.

(42) Nothing had then been written in regard to cohesive construction as applied to the "timbrel arch." This was due to the following circumstance, which is worthy of remark: The nations who for nearly a century and a half were most advanced in scientific and literary work, and who had written most about the applied sciences, were the English, French and Germans, precisely the people who, on account of the erroneous form of their bricks, and the poor method of using their materials, furnished the frequent spectacle, that, when the walls of any of their buildings were torn down and the bricks taken out, they were so nearly clean, without any mortar adhering to them, that they could be used again in new walls. Could the professors and scientific men of these countries have seriously taken into consideration the cohesive strength, although they knew of the existence of some cements? Certainly it is not strange that all conscientious professors were inclined to give coefficients of resistance only for the gravity system, and all their books and teachings were on the gravity system, except for tensions of materials working in that way.

Italy and Spain at this epoch had no text-books of their own; all were translations from the French and English works.

TIMBREL ARCHES.

(43) We will begin by investigating the way in which this kind of arch works.

Fig. 10.

A "Timbrel Vault" of a single thickness of brick or tile (Fig. 10) has no more resistance than an arch or vault built on the "Gravity System"; because, no matter how good the mortar may be, there is only one vertical joint, and the bricks or tiles are working as voussoirs. Consequently this form of arch belongs to the "Gravity System." But if we put another

Fig. 11

course over the first (Fig. 11), breaking joints, and laid with hydraulic material, we will have the action of cohesive force. In this way the mortar laid over the first course, or extrados, takes bond with it, and also with the course laid on top. As soon as the cement sets, we will have shearing resistance represented by

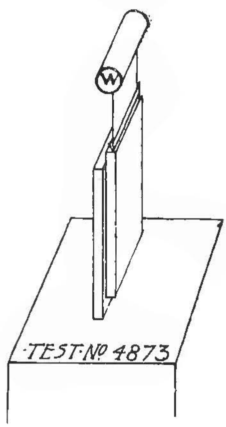


Fig. 12

17,820 pounds per square foot (Fig. 12, test No. 4873). In this way we introduce a new additional strength to the arch which is a peculiarity of the Timbrel Arch System. In the Gravity System (Fig. 10), the strength of gravity alone is the only force keeping the voussoirs in place by pressure against each other in the joints. These joints are not protected, and any reduction in the width of the joints in consequence of pressure, or weight on the arch, *compromises the setting* of the mortar. For this reason in the "Gravity System" the mortar serves only as a cushion, even if cement mortar, because of bad setting, and adds no strength to the arch. But in our "Cohesive System," with horizontal broken joints, with 17,820 pounds per square foot shearing strength, the reduction in the vertical joints is prevented absolutely, as can be proved by the following facts: First, we can build arches of twenty-feet span only three inches thick, using a centre one inch thick, and moving it along as soon as a row of tiles is laid, which usually requires about fifteen minutes. Second, it is common to see the workmen walking over the arch, free from centres of any kind, some hours after it is built; and third, *we can run the centre under the arch again when it is completed, which is the most practical illustration that the arch has had the absolute repose necessary for its settlement.*

(44) These three remarkable circumstances are of great value to architects, as they can be put in the *specifications* and can be depended upon as absolute proof of the safety of the construction.

But this horizontal breaking joint, or new additional strength, is not the only great advantage of the system. There are others, the principles of which we will try to explain.

(45) It is evident that if we were able to build an arch without joints, it would be the best, as it would have no settlement; but as the gravity system has only voussoirs of stone or brick a certain number of joints are necessary.

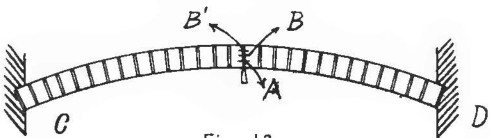


Fig. 13.

Let us suppose that we have a brick arch (Fig. 13) of six-feet span. We would have about 26 or 27 joints of common brick. These joints, being one-quarter of an inch thick, represent about seven inches of mortar, which is compelled to set with all the weight of the voussoirs resting on the centres. The centres, contracting, leave the weight or pressure on the mortar, thus preventing a good setting, and raising the centre of pressure of the arch from A to B (Fig. 13); this happens in all the brick arches, more or less. When this arch rises only ten per cent. of the full span it is very dangerous, because the development of the curve measures very little more than its chord C D. The builder or contractor, knowing this, is always afraid when the centres are removed, and, before the architect knows it, *he brings down the centre of pressure still further*, by hammering in little iron wedges or nails in the joints, covering them with mortar so as not to be seen. This is not good practice, for it destroys what cohe-

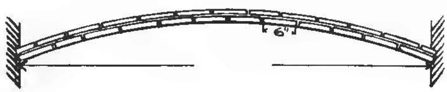


Fig. 14

sion may still be left in the joints, but has the advantage that it prepares the brick for second-hand material by freeing it from the mortar. In our arch, in the same six feet (Fig. 14), we have only 13 joints, one-quarter of an inch each, which is only three and one-quarter inches of mortar; consequently, as we know that the arch with no joints is the best, the one with the least is to be preferred.

(46) There are other advantages equally important. We know that in every arch the curve of pressure changes according to the position of the load; this means that every arch must be

prepared for work by deflection or tension. Let us suppose an arch laid in brick, in such a manner as to receive a test for tension (Fig 15).

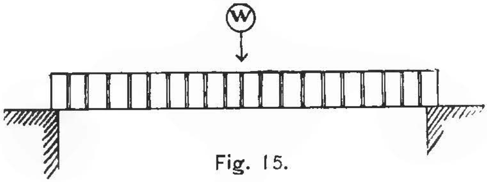


Fig. 15.

The resistance of this tension depends upon the cohesion of the joints, or the resistance to tension of the mortar. But we have observed that this cohesion in the brick arches was very unsatisfactory, and that the mortar is only a cushion in many cases, but that when these joints have a good settlement the tension will only equal the cohesive strength of the mortar between the bricks, and with good cement mor-

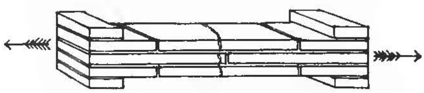


Fig. 17.

tar ten days laid, this strength is only from 80 to 150 pounds per square inch, while we have for our "Timbrel Arch" tensile strength, test

No. 4,875 and 4,876, 287 pounds for ten days, and 159 pounds per square inch for seven days (Fig. 17).

This shows that we have for the cohesive construction the following advantages over the brick arch or any arch built by mechanical construction :

(47) First, the protection of the vertical joints, by introducing the new strength coming from the horizontal breaking joints.

(48) Second, the less number of vertical joints, amounting to only five per cent. of the full span, while the brick arch has ten per cent.

(49) Third, the resistance to deflection (bending-moment), see page 80, "Analysis of some Peculiarities of the System."

(50) The result of these advantages is the surprising strength of the "Timbrel Arches," so that no one can at first understand how 15 or 20-foot arches, three inches thick and with ten per cent. rise, as we said before, can be laid, taking away the centres and giving them over to the uses of the building in a few hours, when an arch of brick with a six-foot span, four inches thick and a ten per cent. rise, requires strong and heavy centres, with several days' repose. Even then this six-foot span, four inches thick and with a ten per cent. rise, is

not a safe construction. The span requires eight inches of thickness, as all architects and builders know.

(51) We may consider, as a safe relation between the brick and "Timbrel Arches," a brick arch four feet six inches in span, ten per cent. in rise, and four inches thick, with cement mortar as is usual in buildings, as equivalent to a ten or twelve foot span in a "Timbrel Arch," three inches thick, and with an eight to ten per cent. rise.

(52) All that we have said about the brick arches in comparison with the "Timbrel Arch" can be applied to the construction of concrete or conglomerate arches, especially in regard to the inconvenience of using heavy centres, and imperfect settlement of the materials. In large arches, the cement cannot be put over the arches quickly enough so that every layer can settle evenly, and the excessive use of the rammer kills part of the cement. That is the reason that for forty years these concrete arches have been tried without success, except in small arches, where the laborers that are generally used in this kind of work can complete the full span of the arch with one single coat having a uniform settlement; but not without always using more material than necessary.

I give an instance of the use of concrete in the foundation of the manufactory of Batllo Brothers: I specified cement concrete for three feet all along the foundation as a first course, putting on top four courses of bricks (6 by 12 by 1 1-2 inches) about the same as we are now using. This was in 1869, twenty-three years ago. I gave orders to lay the concrete six inches at a time. The cement was slow setting for cement, yet I could see some signs of crystallization on the same day. The next day, when inspecting the work of the day before, I found it all a mass of mud. It cost me ten days' labor and many barrels of cement in experimenting with different brands before I ascertained the true cause. It was necessary to adopt a hydraulic mortar composed of two parts lime, two parts sand, and three parts brick-dust, in order to give slow hydraulic mortar, because cement requires repose for a certain length of time in which to set, and this putting it on in a six-inch course and hammering it down so jarred the whole mass that its rest was disturbed and its crystallizing qualities killed. This can be seen in the use of our tiles. Two minutes after the tile is bedded in the arch the cement has begun to set, or crystallize, and cannot be disturbed or used again, when the same cement in the mortar bed will remain several hours without setting.

COEFFICIENTS.

(53) In May, 1877, I commenced a series of experiments in the Department of Tests and Experiments of the Fairbanks' Scale Company, Thomas Street, New York, with the engineer, A. V. Abbott, and I obtained some coefficients. These coefficients are as follows: —

No. 4817, May 3, 1887, compression test, sq. in., 5 days,	2,277 lbs.
No. 4818, May 3, 1887, compression test, sq. in., 5 days,	1,624 lbs.
In the last the heads were not even.	
No. 4869, June 6, 1887, compression test, sq. in., 5 days,	1,43 .
No. 4870, June 6, 1887, compression test, sq. in., 5 days,	2,911 lbs.
	8,242 lbs.

$$\frac{8,242}{4} = 2,060 \text{ lbs.}$$

No. 7475, Oct. 22, 1889, compression test, sq. in., 1 year, 3,290 lbs.

Transverse (Fig. 16). (Page 60.)

No. 4871, June 6, 1889. 90 lbs. per sq. in.

Tension (Fig. 17).

Test No. 4875, Jan. 7, 1887. 287 lbs. per sq. in.

Shearing Stress (Fig. 12).

Test No. 4873, June 6, 1887, in Portland cement, 8,910 lbs. = 123.7 lbs. per sq. in.

No. 4872, June 6, 1887, in plaster-of-Paris, 2,450 = 34 lbs. per sq. in.

GENERAL FORMULA FOR SEGMENTAL ARCHES.

(54) $T\,C = \frac{LS}{8\,r}$ (1) for distributed load.

(The explanation of these formulas will be given later.)

L = Load in pounds including material. (L is always 12″ in length × span and × load in lbs. per superficial foot, including material.)

R = Resistance in middle of arch, or T × C.

C = Coefficient for compression = 2,060 lbs. per sq. in., breaking load.

C′ = Coefficient tension = 300 lbs. per sq. in., breaking load.

C″ = Coefficient transverse = 90 lbs. per sq. in., breaking load.

T = Area of cross-section, in superficial inches, in the middle of the arch. (T will always be 12 × thickness, or area represented by 12 = thickness.)

r = Rise of arch in feet.

S = Span in feet.

(55) We use the formula (1) to get the thickness necessary at the centre of the arch with a distributed load, including the weight of the arch itself. After that we find the line of the

extrados of the arch in a graphical manner, derived from the formula given by Dejardin for tracing the equilibrium profile of the extrados for the vaults, giving the section of the arch in the skewbacks, or base of the arch on each side.

(56) This formula is (2) $V = X \frac{e}{cos.\ a}$ and is the general one for any semicircular or segmental arch, but making for the first case

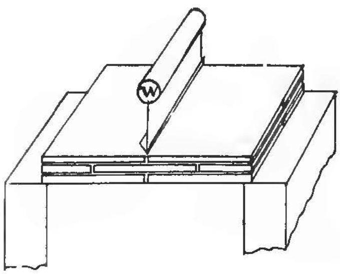


Fig 16.

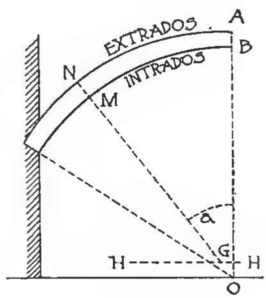


Fig. 18.

$a = 60°$ for the segment of an arch; a equals the degrees corresponding to one-third of the segment in which V is the radius vector of the extrados O N (Fig. 18).

X is the radius of the intrados O M.

e the thickness in the centre, or A B.

a the angle that any radius makes with the vertical O A.

Hence the complete formula is

$$(3) \quad \frac{L\ S}{8\,r \times 12\,C}$$

which represents the thickness of the centre of the arch in inches, or

$$\frac{\text{area of 1 foot arch in length,}}{12}$$

and

$$(4) \quad \frac{L\ S}{8\,r \times 12\,C} + (V - (X + B\,A) \text{ for the}$$

thickness of the spring of the arch in inches.

(57) The graphic procedure is as follows (Fig. 18):

Take the thickness T, or, say A B, and lay off O H equal to it; draw H′ H parallel with the chord O K, draw O N through the point M, which is one-third of B M′—.

Lay off M N = O G, N gives us one point of the curve of the extrados. See Fig. 18. As N M is the weakest part of the arch, we can safely put the same thickness at the spring which gives us the third point that is necessary to trace our curve.

(58) With the same formula we can find the thickness of the arch necessary for a single load at the middle, but making $4\,r$ instead of $8\,r$.

We now come to the problem of a load on any point of an arch.

(59) The remark has been made that these kind of arches cannot be used for a moving or concentrated load. We know that if an arch is built with the condition that the curve of pressure is inside of the middle third, the arch is safe; starting with this we apply the general formula for finding the thickness in the centre, and we trace graphically the curve of pressure as shown in Fig. 19, as if the load was resting on point 11. That gives a lower line of pressure than any other point for one side of the arch, and when the load is on a corresponding position on the opposite side, the same curve reversed gives us the whole arch.

Now it is necessary to put half the thickness given by the formula on either side of the line of pressure O, O′, O″. Fig. 19, forming the lines X, X′, X″, Z, Z′, Z″, that represents the total thickness of the arch. With this, as we have said, we have the thickness of the arch necessary for the lowest line of pressure required for any position of the load.

When the load is on 11, the pressure is passing through the imaginary lines 11 C and 11 *e;* when the load is on 10, the pressure is passing through the imaginary lines 10 *a*, 10 *c′*, etc. Consequently it is inside of this area, between the level of the floor and the line of lowest

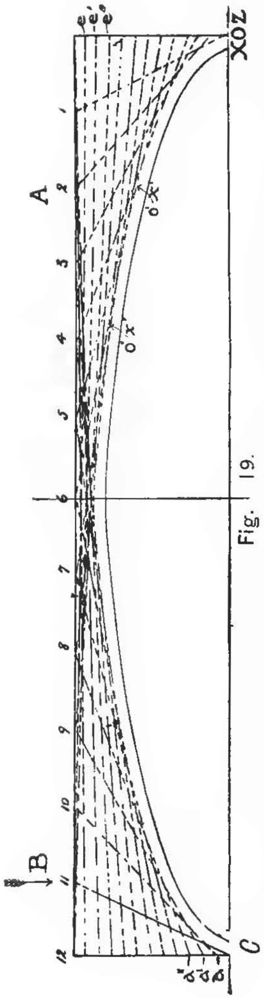


Fig. 19.

lines of the arch (Fig. 19) where the curve of pressure rests; that means that if we fill up solid, *or in such a way as to take the place of solid materials*, as, for example, in tubular girders, we are sure that the curve of pressure will always be inside of the arch.

(59) We say, *or in such a way as to take the place of solid materials*, because in practice it is better to avoid the enormous weight of this unnecessary mass of material, and, besides, to avoid the condensation that such a mass of material accumulates in the ceiling, by building the lower part of the arch X′, X″, X‴, and Z′, Z″, Z‴, and over that building bridges at a sufficient distance (generally two feet apart), and over

these building again a flat arch of the same thickness as the arch below, forming in all, by this construction, a regular tubular arch, light, dry and well ventilated, and with sufficient strength in every part.*

(60) Take for example an arch with a 15 ft. span, and a 10% rise, that must support 250 lbs. per square foot, including material† and distributing load.

$S = 15$ feet.
$r = 1\frac{5}{10}$ feet.
$C = 2{,}060$ lbs. per sq. in.
$L = 250$ lbs. $\times\ 15 = 3{,}750$ lbs.
As the load is distributed,

$$T\,C = \frac{3{,}750 \times 15}{8 \times 1.5} = 4{,}687.5, \text{ and } \frac{4{,}687.5}{2{,}060} = 2.275$$

But we are working at 10% breaking load and $T = 22.75''$ (twenty-two $\frac{75}{100}$ superficial inches), or an area $12'' \times 1.9''$ or $1\frac{3}{4}$ tiles; two courses will be used, making $2'' \times 12'' = 24$ square inches.

But with this we have only the thickness necessary in the middle of the arch.

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* One example of this is the section drawn for the projected bridge at Prospect Park, Brooklyn, by the architects, Messrs. McKim, Mead & White.

† That weight must be considered as a distributed load.

(61) To find the thickness for the spring, we shall have to determine the extrados N′ A′ *c* (Fig. 20) by the graphic method devised in the formula of Dejardin, or by the formula (4); we

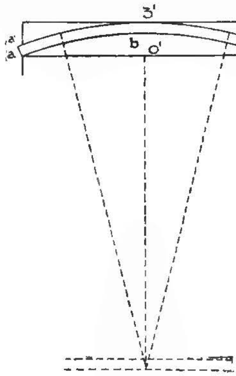

Fig. 20.

thus find that T in the spring is about 12″ × 2.26″ or, 3 courses, inside of 12″ × 1.9″ and 12″ × 2.26′ or, 3 courses, or, 3 inches, must be adopted in order to increase the resistance to bending moment * in the haunches of the arch. Two and one-half inches is enough, but it is better to give the half-inch in excess, to be on the safe side, because no thinner tiles are made

* We give, at the end of this book, a table taking in consideration the bending moment (see page 148).

to adjust the thickness, and it is preferable to make this allowance, thus increasing the section at the base of the arch, laying three courses in the sides and two in the centre.

DOMES.

(62) The dome is the genuine form of the cohesive construction for ceilings, floors and roofs, as well as for timbrel arches.

(63) We use the following formula for distributed loads :—

(5) $\frac{L\ S}{8\ r \times 12\ C \times 2}$ for the thickness on the crown. ($L =$ Span $\times$ 1 foot $\times$ weight in lbs. per superficial feet including material), and

(6) $\frac{L\ S}{8\ r \times 12\ C \times 2} + \Big(V - (X + 2\ B\ A)\Big)$ for the spring in inches, not taking into consideration anything but the pressure.

(64) Practically we can have the same result by using formula (1) to get the thickness necessary at the crown, as in the case of the barrel or segmental arches. Afterwards take from the crown and from the spring half of the thickness given by formula (1), or else deducting $\frac{L\ S}{8\ r\ 2}$.

(65) Example:

$S = 40.$

$r = 4$ feet.

$C = 2{,}060$ lbs. breaking load.

$L = 250 \times 40 = 10{,}000$ lbs.

As the load is distributed,

$$T\,C = \frac{10{,}000 \times 40}{8 \times 4} = 12{,}500, \text{ and } \frac{12{,}500}{2{,}060} = 60,$$

taking 10% of the breaking load, and as we count only a piece of the dome 1 foot or 12 inches in length, $\frac{6}{12} = 5$ inches. Now to find the additional thickness, or, to trace the equilibrium profile of the extrados, we will provide the same as in the case of example (60) for the segmental arches. We will find that the increase in the spring is about 2″ or 7″ in all. Now we must take off

$$\frac{\frac{L\,S}{8\,r}}{2} \text{ or } \frac{\frac{10{,}000 \times 40}{8 \times 4}}{2} \text{ or } \frac{\frac{12{,}500}{2{,}060}}{2} = 3 \text{ breaking load,}$$

30″ safe load, and $\frac{30}{12''} = 2\frac{1}{2}''$. So we must take away 2″ from the thickness of the dome. Now as the thickness was 5″ in the crown and 7″ in the spring, taking off 2″ will give 3″ in the crown and 5″ in the spring.

(66) Explanation of the formula :

We do not pretend to have an absolute mathematical formula, but a practical one, enough to insure sufficient security for safe construction.

We may add that these formulas and theories, if not founded absolutely on the known and admitted theories of the " Gravity System," are nevertheless on the principles admitted for all kinds of cast bodies, and I thought it better

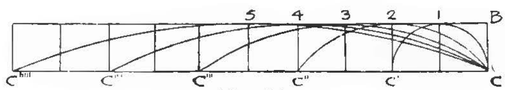

Fig. 21.

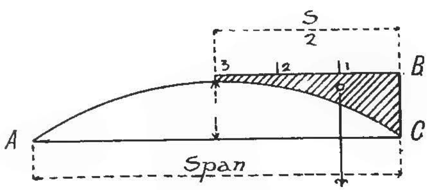

Fig. 21 bis.

to put them in the form commonly used, to make them more clear, and avoid strange ideas which serve to confuse the mind, before explaining their different forms of working exclusively within the theory of the cohesive system, which we will explain later.

(67) We consider our arch not as an arch with voussoirs, but as a single cast arch, working as a solid piece of arched stone or iron.

Suppose, now, we make a solid piece of material of the form 1 B C (Fig. 21), without taking into consideration its weight, the curve 1 C, being half of a segment of an arch, and at C a *pivot*. Applying 10 tons on the point 1, we find by the law of mechanics, that, having B C = B 1, we need, at the point I, a horizontal pressure of 10 tons for equilibrium.

(68) Let us pass the 10 tons to point 2, that is, an arch of which the span C – C″ (Fig. 21) is 4 times the rise; as B 2 is double B C, the equilibrium of the 10 tons vertically at the point 2 must be, $10 \times 2 = 20$ tons applied horizontally.

We now pass the 10 tons to the point 3; that is, an arch of which the span is 6 times the rise, and we will find that for equilibrium it will be necessary to multiply $10 \times 3 = 30$ tons. The same holds good when we pass to No. 4, which will be forty tons, and to No. 5, which will be 50 tons: that is, in an arch with a rise of ten per cent. of the span, we have a pressure in the middle five times the weight of the single load.

If we double the figure, that is, the full arch C A (Fig. 21 bis), and we consider the same load of 10 tons, at the point 3 for each half, and if we consider the *pivot* at the places C and A, as both form a single arch, we will have the pressure in the middle of the arch one-half as much as before, or 30 for either side, and the real pressure, between the two heads, will be the full 30 tons and no more.

(69) With this we find out, that in any single load over an arch, the thrust is divided equally on both sides; but in the middle section of the arch we have a pressure one-half of the full load. This shows that the section in any arch, independent of its own weight, and only taking into consideration the weight of the load, will be the same as that of the section on either spring, and the section on the crown will be

$$T\,C = \frac{\text{Load}}{2} \times \frac{\text{Span}}{2} \text{ for concentrated load,}$$

$$\text{or, } T\,C = \frac{\frac{\text{Load}}{2} \times \frac{\text{Span}}{2}}{r \times 2} \text{ for any distributed load}$$

replacing B 1, B 2, etc., in every case by $\frac{\text{Span}}{2}$ and B C by r, the rise of the arch, and,

$$\text{simplified, } T\,C = \frac{\text{Load} \times \text{Span}}{2\,r} \times 4$$

$$= \frac{\text{Load} \times \text{Span}}{4 \times 2 \times r} = \frac{L\,S}{8\,r}.$$

(70) These general expressions, $\frac{L\ S}{8\ r}$, which represent, in all cases of distributed load, the pressure in the middle section of an arch in relation to the span and rise, are equal to the area multiplied by the coefficients of resistance of the material of which the arch is built.

(71) We represent this area by T and the coefficient by C, and T C = resistance.

Now T = area of the section, and as we always take 12″ in length of the arch, or 1 foot, in order that the load considered may be applied only on each superficial foot all along the span, $\frac{T}{12}$ = thickness of the arch.

Now $\frac{T\ C}{12} = \frac{L\ S}{8\ r\ 12}$ or $\frac{T}{12} = \frac{L\ S}{8\ r \times 12\ C}$ or,

thickness $= \frac{L\ S}{8\ r \times 12\ C}$.

The expression $+\left(V - (X + B\ A)\right)$ comes from the well-known formula of Dejardin, for tracing the equilibrium profile of the extrados for vaults to $V = X\ \frac{e}{cos.\ a}$.

(72) If in addition to the expression $\frac{L\ S}{8\ r \times 12\ C}$, we put the thickness to reinforce

the extrados, we must add to the thickness we already have the difference between the radius of the extrados in the centre, that is, $X + A B = o A$ (Fig. 18), and the radius vector $V = o N$,

$$\text{or} + \Big(V - (X + B A)\Big),$$

$$\text{or} + \left(\frac{e}{cos.\ a} - (X + B A)\right).$$

(73) Explanation of the formula for domes.

$$(5)\quad \frac{L S}{8 r \times 12 C \times 2}.$$

$$(6)\quad \frac{L S}{8 r \times 12 C \times 2} + \Big(V - (X \times 2 B A)\Big).$$

We must repeat here that we do not pretend to have an absolutely mathematical formula, but one practical enough to give sufficient security for safe construction. We are here also considering the dome as not one of voussoirs, but as a simple cast dome working as a single piece.

(74) The formula (5) is the same as that of the barrel arches (1) with the difference that (5) formula gives the thickness only and not the area $\times$ T C; area $\times$ coefficient is transformed into $\frac{T C}{12 C}$ and $\frac{T C}{12 C} = \frac{L S}{8 r \times 12 C}$ and as L represents a portion of the arch 12″ in length, multiplied by the weight in lbs. and also by the span, and as the surface of any symmetrical

portion of a dome is just half of the surface of any symmetrical portion of a barrel arch of the same radius and base, L in the dome will be just half or $\frac{L}{2}$;

hence $\frac{T\ C}{12\ C}$ in the dome $= \dfrac{\frac{L\ S}{8\,r \times 12\ C},}{2}$

or $\dfrac{L\ S}{8\,r \times 12\ C \times 2}$

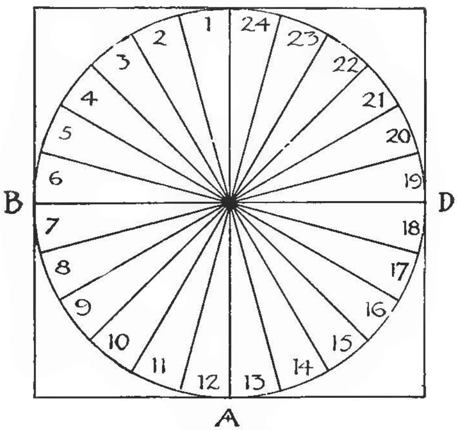

Fig 22.

(75) Domes in the Cohesive System cannot be considered as a modification of the barrel arch but as an absolutely different constructive member for covering spaces.

(76) I.—The surface of a dome is just half the surface of any barrel or segmental arch of the same radius having for its length half of the circumference of the base of this dome, with the peculiarity that the surface is decreasing in direct ratio that it approaches the crown. In effect:

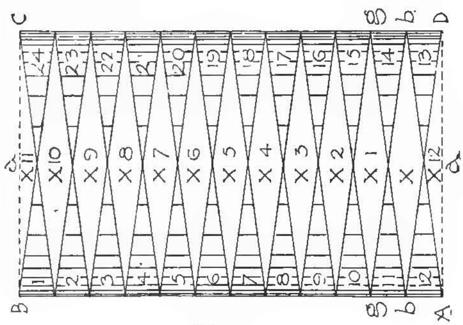

Fig. 23.

Taking the plan of a dome (Fig. 22) and dividing it into small radiating portions 1, 2, 3, 4, etc., so that each portion can be considered as the smallest expression that can be divided, and afterwards supposing there are built with these portions a segment of arch of the same curve as the dome, but in portions (as in Fig. 23), having the base of half the portions of the dome in a line B A, and the base of the other half of the portions in C D, we shall have an arch, but with openings $X\ X'\ X''\ X''' \ldots\ldots X^{12}\ X^{13}$. We will notice that the surface $1 + 24 = X^{10}$, then $2 + 23 = X^9$, $3 + 22 = X^8$, etc., and that $X + X' + X''$, etc., $=$ surface $(1 + 24) + (2 + 23) + 3 + 22)$, etc.; but as surface $X +$

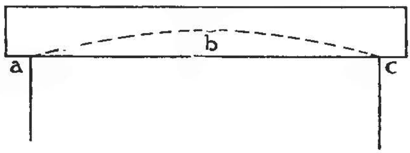

Fig. 24.

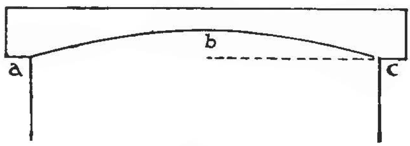

Fig. 25.

$X' + X''$ are all open spaces and no load can be considered, L of the expression $\frac{L\ S}{8\ r}$ will be

$$\frac{\frac{L}{2S}}{8\ r} \text{ or } \frac{\frac{L\ S}{8\ r}}{2} \text{ or } \frac{L\ S}{8\ r \times 2}.$$

(77) 2. — The material of a dome is not only working by compression, but in consequence of

its form it is also working by tension, because *the thrust depends upon the form and not on the material.* Suppose we take a lintel of stone, as in Fig. 24; if we put it as in Fig. 24 we have practically no thrust. If we take another lintel (Fig. 25), that is like the first one; but, taking off the material under the curved line *a*, *b*, *c* (Fig. 25), we have some thrust at once. We can see without any demonstration, that in the second case we have thrust and in the first one we have comparatively none. This does not mean that in the first case it absolutely does not exist, because inside of any lintel we must consider an arch when it is working; in the same way that in any block of stone, or any block of marble, or any block of wood, we know the most ideal figure exists that the imagination can conceive. The question is to take away the shell that encompasses it. In the same way, in any piece of wood, or in any block of stone, we have an arch better than any which the most exact mathematician can define; and, as soon as we put a lintel to work, this imaginary arch is put into action, and all of the material under this arch is working to take off the thrust, *because it is the rod of this imaginary arch.* Now, if we take away this material (which is the condition in the second case), as the material which is working as a rod is not there, the arch is more free for weight and thrust.

(78) But we have a third case, as in Fig. 26. This is not a lintel where we take the lower part of the material, forming, as in the rest, an arch. It is a regular arch, formed by pieces. It is not necessary to demonstrate that this has thrust; but in this case the thrust is in full, if I may use the term. I mean in full

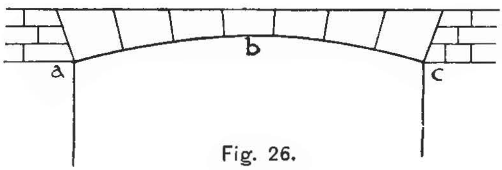

Fig. 26.

because in the second case, the stone lintel, being cut in a curve, is not as free as in the third; because, to get any signs of thrust, it is necessary to break the lintel. Consequently, the effect of the thrust begins when the cohesive resistance of the stone is overcome; whereas, in the third case, this commences at once, because it is in several pieces and there is no cohesion. *Our barrel arches are working in the second case.*

(79) Considering the case of domes, suppose we have (as in Fig. 27) a dome composed of voussoirs. This dome will have thrust, because it is a modification of the segmental arch of voussoirs (Fig. 26).

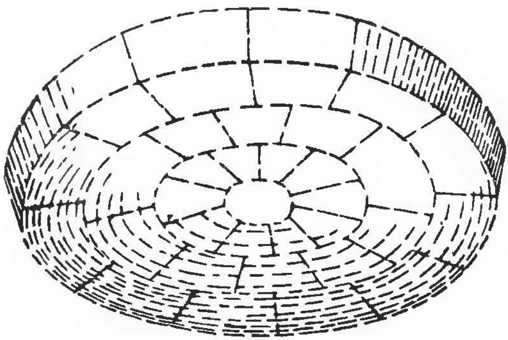

Fig. 27.

Now suppose we take (see Fig. 28) a big block of stone, say ten feet long and ten feet wide, and one foot or one foot six inches thick. If we support that on the four sides just as a lintel, we have practically no thrust, and if we make a cavity on the under side (Fig. 29), making a curve like a dome, we will have a dome arch, but no thrust. It is not the second case of the lintel, where, taking off the material *that is working as a rod, the thrust commences* *to act.* In the case of the dome it is not so, because the material that is working as a rod,

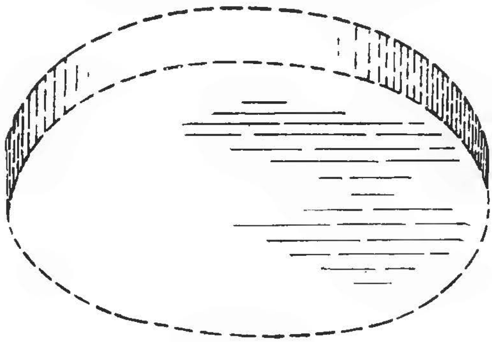

Fig. 28.

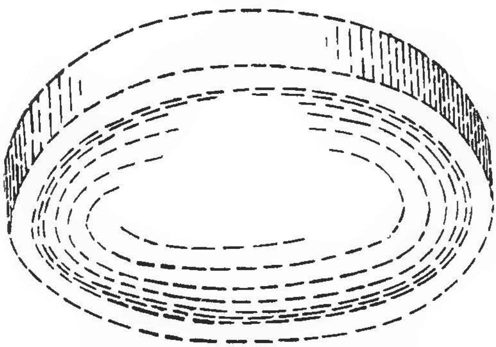

Fig. 29.

or by tension, *is formed into rings which remain as rings.* This is our case; if we build the ceilings in the form of domes, and if they are well applied and properly built, we have, practically, no thrust whatever.

THEORY OF THE COHESIVE CONSTRUCTION, BASED ON THE THEORY OF THE COHESIVE ELEMENTS.

Analysis of some peculiarities of the system.

(80) Before proceeding further, I would like to make a few preliminary remarks, calling attention to some essential and peculiar principles of the Cohesive System applied to the supported members. They are not new as technical matters, but they are not taken into consideration to-day in ordinary construction, and cannot be explained by the voussoir theory.

Fig. 30.

Fig. 31.

In any ceiling composed of cohesive barrel arches supported between beams, the less the radius of the curve of the arch, the less the beams have to bear, and consequently the lighter the beams need be.

(81) This means that a ceiling composed of cohesive arches built as in Fig. 30 will support

more weight than one with the same beams and spans as in Fig. 31, in which the arches have more radius. This principle, at first thought, seems absurd, in consequence of the extra material used, because the arch has greater surface and brings more weight to bear on the beams. That this is true will be shown hereafter.

Fig. 32.

Fig. 33.

Suppose Figs. 32 and 33 have an arch with a radius at infinity, or flat, the neutral axis is XX' transverse section. The material situated below the neutral axis will work by tension, and that above by compression, and having in our case, say only about three courses, or say three inches in thickness, the moment for tension will be, one inch and a half, and for compression one inch and a half.

(82) Suppose Fig. 34 to be an arch whose rise is a foot. The central axis will be X^4 X^5. The part below it, working by tension, will have six inches for its moment, and that above the

same. All this part, worked by tension and compression, acts really as a second beam, taking part of the load off the iron beam.* To

Fig. 34.

find the extra strength that this form of arch adds to the construction, of which it forms part, — as it depends upon the tensile strength of the material, which is 223 lbs. per square inch, — we can apply the following formula, represented by

L = Load in pounds.
S = Span in feet.
r = Rise in feet.
C = Coefficient 223 pounds breaking load.
T = Surface area in square inches.

$$L = \frac{8\,r\,C\,T}{S}$$

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* It can also be reinforced by means of a counter-arch turned over the beam, which arch will take part of the load of the floor and transfer it against the walls which are tied by the said beams, so that the beams will act in connection with this arch by tension. This disposition has the advantage of reducing the concreting, and in consequence the weight, over the haunches of the arch and beams.

This will be the breaking load; the beam must be strong enough to add to the strength of the arch sufficiently, so that it can never work up to its breaking load.

In any ceiling composed of barrel arches constructed on the cohesive principle of construction, supported between beams, the ends of the beams and the extremity ends of the barrel arch receive the principal load and in consequence the beams receive least weight in the middle.

(83) Suppose Figures 35, 36 and 37 are barrel arches built over two beams, the beams supported by two lateral walls. Let us consider two diagonal arches, *a*, *b*, *c*, *d*. Any load uniformly distributed over the arches will affect

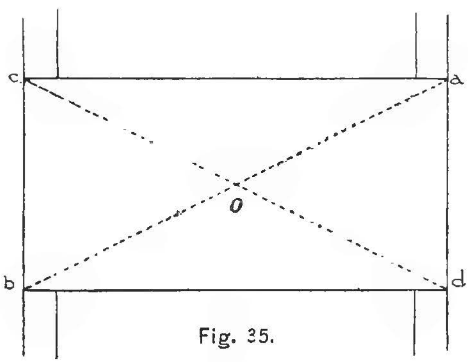

Fig. 35.

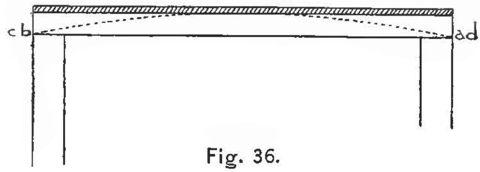

Fig. 36.

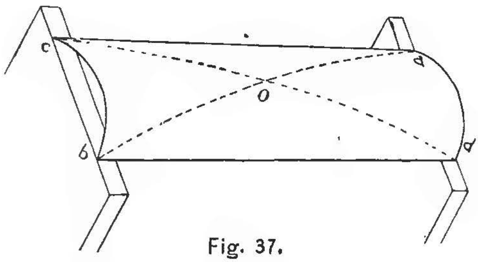

Fig. 37.

evenly every point of the skewback that is over the flange of the beams; but as the points *a*, *b*, *c*, *d* are the most rigid ones, they will be the first to sustain the weight of the arches, consequently helping the beams,* and establishing the lines of pressure *a* and *b*, *c* and *d*. (See Figs. 35 and 36.) Similar arches will be formed from the point *a* to the opposite diagonal *c*, and from

* The *a*, *b*, *c*, *d* arch referred to in Fig. 35 will have on plan the form of a parallelogram limited between the lines of pressure A, O, C, and the similar lines of the next adjoining arch (Figs. 35 and 37).

d to the opposite diagonal *c*, a tendency that will also be similar to the principles mentioned before.

(84) Fig. 38 represents a barrel arch broken irregularly and diagonally in two. In practice, the timbrel arch of this form retains its equilibrium, which cannot be explained by the

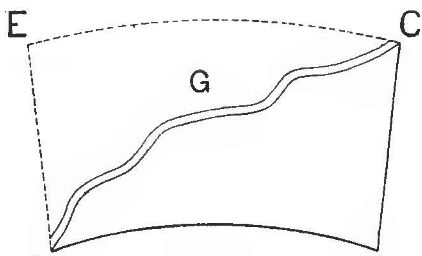

Fig. 38.

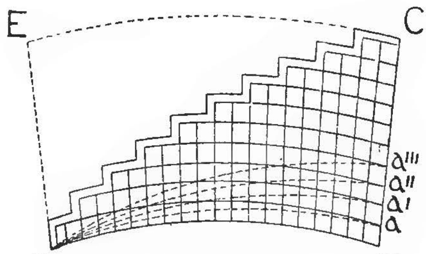

Fig. 39.

voussoir theory. In the voussoirs that begin in the line F, C, Fig. 39, the first ring F, D, has two skewbacks, but the second ring a' has but one. The same is the case with a'' a''', etc., and according to the gravity system the arch is not admissible — it is not safe. But in our system we know that this arch will stand, because we see it stand every day. All we do is to reinforce the point D, arching in radical form from the point D to the opposite line F, C, or skewback forming the coniform *cohesive elements*, F D a', a' D a'', a'' D a''', etc. (Fig. 39), and add it to the other. Thus, the element b, b', b'', etc. (Fig. 40), resting on the skewback C, F, will be accumulated at the point D.

If we construct in addition to this broken barrel arch (Fig. 38, plan Fig. 40) the portion E, G, C (Figs. 38 and 40), we shall accumulate the element b, b^{I}, b^{II}, b^{III}, b^{IV}, b^{V}, b^{VI}, b^{VII}, half to the point D and half with the point E, having a perfectly safe arch, such as we are making in the ground arches, and the sum of the cohesive elements, along the line or skewback F, C, must be equal to the sum of the elements accumulated in the point D and the point E.

(85) It may be remarked that the empty space E, G, D (Fig. 40), not having any load on it, it seems that we can economize the elements

b, b^{I}, b^{II}, b^{III}, b^{IV}, b^{V}, b^{VI}, b^{VII}. But we may notice that the part of the elements radiating from F to C are cut for the opening D, G, E, and they must suffer a deviation pursuing the same devi-

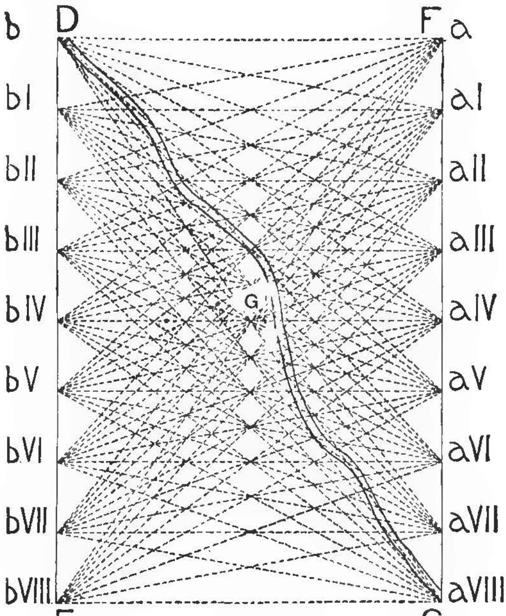

Fig. 40.

ation as the elements b, b^{I}, b^{II}, etc., when they are directed to the point D and E.

(86) Any of these examples cannot be explained by the voussoir theory and gravity

system, and I suppose they are sufficient to illustrate in this *essay* the incompatibility of these theories with the results of actual experience. I think it is more rational and simple to explain these applications by the cohesive strength of the materials used, and in consequence why not explain the theory of the cohesive arches by the theory of *cohesive elements?*

If we build Figure 41 of stones placed one on top of the other, anchoring the base, the force of gravity alone keeps them in place, and any horizontal pressure, P, must be resisted by the weight of each piece, there being no other force which can help the full construction.

(87) To illustrate this

let P = the horizontal pressure

r = the distance of its point of application above the joint $a\ a'$

W = total weight above a

T = the breadth of $a\ a'$;

then taking moments about a' we get the equation

$$P\,r = W\frac{T}{2}$$

(88) But if we construct the figure of cohesive material (Fig. 42), the horizontal pressure, P, will be not only the gravity, but also the cohesive strength, of the material to overcome.

This refers to vertical construction on a solid base.

Making the same investigation with regard to Figure 42 as we did above, we must take into account the cohesive strength of the material

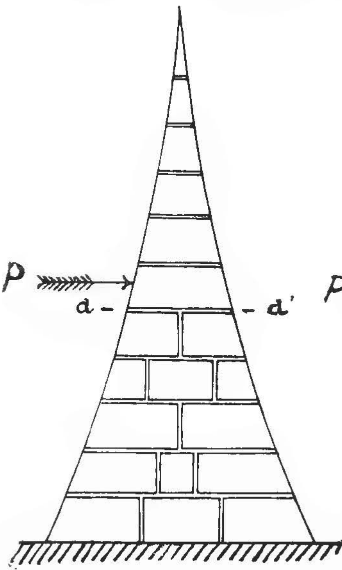

Fig. 41.

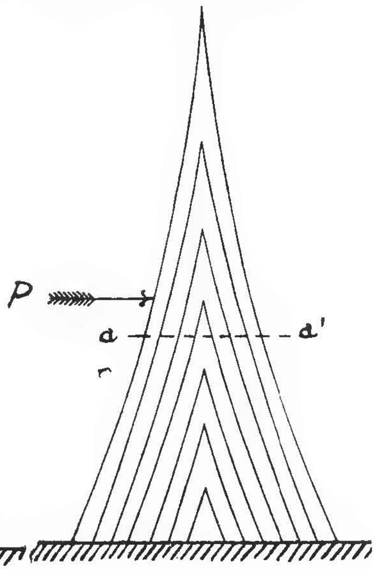

Fig. 42.

which resists tension at a and compression at a'. If the strain developed at each of these points $= C$, then $P r = W \frac{T}{2} + C T$.

(89) For a horizontal construction in space, if we suppose a structure like Figure 43, built with voussoirs, we can readily see that its construction would be impossible, as the joints

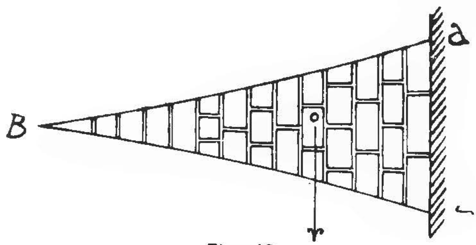

Fig. 43.

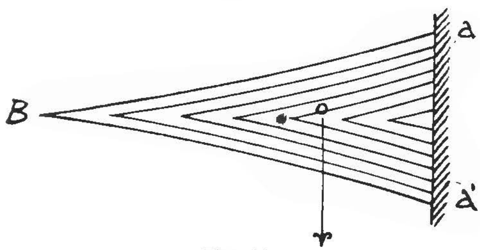

Fig. 44.

have no cohesive strength, and its weight would make it fall at once. But with cohesive material we can build a structure like Figure 44 in such a way that the cohesive strength of each particle of the structure will resist the force of gravity acting on that particle. To analyze this construction let S = span = B a' and then, as the centre of gravity is nearly one-third of the span from a horizontal distance from the centre of gravity to the section a a', let W = weight of the structure, which in this case tends to produce rupture at a. Taking moments as before, we obtain the expression $W \frac{S}{3} = C\ T$.

In this case we see that the expression $W \times \frac{T}{2}$ disappears, but we have the force resisting rupture, that is, the cohesive strength of the material, or $W \frac{S}{3} = C\ T$.

(90) In Figure 41, representing the Gravity System, we build with blocks from the quarry having cohesive strength in themselves, but with no cohesion between them, acting only by gravity.

(91) In the second case (Fig. 42), we also use material having life in itself, making it into a homogeneous structure, having the same properties throughout as in a monolith, thus imitating the action of nature in the quarry.

(92) The third case cannot be considered, because such a form cannot be constructed

with voussoirs on the gravity system; and in the fourth we have the plain work of cohesion.

(93) Comparing these four figures, we see the advantage of working with live material; that is, with material which has in itself properties of cohesive strength. And we may observe that the minimum strength will be when the material is working only by deflection, or when not all of the section is working by pressure, or else when the position is horizontal (Fig. 44), that is, when $r = O$. And the maximum will be when the material is working principally by pressure or when $r =$ *infinity*, that is, when the sides of an arch are practically two walls.

(94) But at the moment that r (in Fig. 44) commences to have a finite value we will have both tension and compression acting to maintain stability, and the greater the value of r the more will the compression act and the less the tension be. Consequently we must have two coefficients, one that we can call C for compression and another C′ for cross-section or modulus of rupture. The formula for the first is:

$$\mathrm{T\,C} = \frac{\mathrm{L\,S}}{2} \text{ and for the second } \mathrm{T\,C'} = \frac{\frac{\mathrm{L\,S}}{6}}{r}.$$

The expression $\frac{S}{6}$ results from the following (Fig. 42): $S =$ the span and the $\frac{S}{2} = \frac{1}{2}$ the span, but as we are considering only the weight of the material, we know that its point of application $= \frac{1}{3}$ of $\frac{S}{2}$ or $\frac{S}{6}$.*

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*I shall not go into further details about this theory and its universal application in new ideas of construction because it is not within the limits of this preliminary and small book.

PART IV.

MODERN APPLICATIONS AND ARTISTIC OR ÆSTHETIC IMPORTANCE OF THE COHESIVE CONSTRUCTION.

(95) It is said, and generally understood, that the art of construction in masonry is as yet in its infancy, and that we are not out of its first rudiments. Perhaps these ideas are based upon the fact that the technical data we possess to-day for this kind of construction, which is being generally taught in our colleges, are little advanced beyond those which were employed in constructing the edifices of 1000 or 2000 years B. C.; that is, those used by the Egyptians and others.

(96) It is true that, with the arrival of the romantic epoch, that is, when the architectural art, having gained consciousness of its independence, was reproducing to infinity its architectural theme, we find works that we yet admire as models of construction and art, including those outside of the construction depending on gravity; but none of the constructive sciences

admit as yet that they are but plain general construction, and but few architects are disposed to risk their signatures to them, and those that do only admit the outside lines. Why? suppose an architect intends to build a structure with a combination of domes, as in either the cathedrals of Santa Sophia, in Constantinople, or Zamora, in Spain, and sends plans of it to the Building Department for approval in one of our large cities. He will find it a most difficult matter to obtain a permit to build this structure, and in consequence he will have to make an imitation of the outside and inside artistic lines by a false construction. What does this mean? Are we progressing, or is our knowledge inferior to that of the Middle Ages?

(97) Perhaps this can be explained in the following manner:— The builders of the romantic epoch, when they were building, were making architecture; they were builders, architects; they were making plans which they themselves would carry out; they were, in a word, builders and architects, and could not be in any other way, because those innumerable, great, architectural conceptions of the Middle Ages were not possible to be realized, unless the same genius who designed should build them. So that to-day we do not know which to admire

in those monuments most, — the architectural lines or the successful constructive problems solved.

(98) It is true that they were not restricted by any building laws, being the builders and architects both, or *vice-versa.* And their full liberty in building was a great advantage to the architectural art in two ways : it was advantageous to the progress of construction, and also to the artistic side, because the work of an architect should not be the plans alone, but the building itself ; the plans are the project and the work is the building. Is it then strange that the history of art admits that one of the most brilliant epochs of originality in architecture was in the Middle Ages ? In their dwelling-houses, palaces, city-halls, chambers of commerce, churches, convents, fortresses and cathedrals we cannot surpass their work, either in beauty or engineering skill. We cannot say that of modern times, with the exception of our great iron bridges, depots, etc.

(99) The architect of the present epoch, especially in this country, for reasons that cannot be discussed here, generally makes plans which are to be built by some one else, and the constructive parts given by the building laws are official data. It is not necessary for

him to think to any great extent of problems of construction, and he loses in consequence, day by day, consciousness of the fact that he is a real architect as was formerly understood by this generic word.

(100) On the other hand, the builder, that is, the one who carries out the plans of the architect, is not only, by his character of a simple builder, *forbidden* to understand anything of the architect's part, but he cannot modify any part of the constructive problem; not only as a matter of financial policy to himself, but also from the fact that he is not, as a rule, a man of study, having only some ideas of materials, the general trades, and scaffolding, and enough knowledge, perhaps, for estimating.

(101) The result of this anomalous combination is a very strange one. In the first place, the feeling is, that the work of an architect is to make the plans, and take the direction of the artistic part, and also that the problem of construction must be on a level with the general knowledge of the contractors; and the architect, in order to be free from difficulties, makes the specifications and general conditions of construction in accordance with the official formulas, and according to the intellectual abilities of the builders. Now, this

being the general *modus operandi* in nearly all kinds of building, it is evident that, although the so-called artistic part may be in some cases highly studied, if not developed, by the architect as a designer, the constructive progress, the real architectural progress, is obstructed by two fortresses; namely, building laws, and the contractor's financial policy. In consequence, it may be thought, with some sort of reason, that, for making plans for a building, it is not necessary to learn construction.

(102) This puts me in mind of the following anecdote: Rossini one day asked his Professor if it was necessary to learn counterpoint in order to learn opera composition; and the Professor, thinking only of the modern Italian opera, answered, "no."

It is to be hoped that some radical change will follow the present state of things, in order to assist in redeeming the art from these ignoble and servile conditions.

APPLICATIONS.

(103) In speaking of the "Cohesive System" applied to "Timbrel Arches," of which this book specially treats, I am aware that, even to the initiated in the science of construction, it might occur that this system can only be

applied to arches, as it has been applied in the construction of the arching floors of the new Boston Library. This system is not confined to the specialty of the vault, neither is it placed in exclusive competition with brick arches, but it consists of a complete system of construction, including walls, floors, roofs, ceilings, partitions, staircases, columns, etc.

(104) The great and surprising advantage of the "Timbrel Vault" over the brick arch will be found equally in walls, roofs, partitions, etc.

FLOORS AND ROOFS.

HOW THE MATERIALS WORK IN THEM.

(105) It is evident that the use of light materials of equal strength, each material used in the way required by its nature, is the basis of building economy. If we put the wood or iron to work under deflection, or submit them to transverse pressure, surely we shall need more material than in using the same wood or iron under tension. If we place them in this position we will have an economy. The same is true when we put clay and cement to work by pressure; they then have their greatest efficiency, and can replace iron and wood with economy. In a floor in the ordinary system

we find wooden or iron beams, and between, wooden boards or brick arches. What are the wooden boards and brick arches doing? Only bridging between the girders or beams. All the material between is not working at all; the total weights are supported only by the beams or girders, and these bridges contribute only to the weight. But in the Cohesive System, if well applied, every piece of material is working directly, and just as is necessary; the clay works to support itself, working by pressure, and the iron works as a rod. That is the great economy. All will admit that, with these conditions, it is not strange that this system, although the material itself is dearer, can compete with advantage with any system.

(106) For many reasons the ceiling or roof is the most difficult part of the project of any building; and to this the architect generally gives his attention, knowing that any excess or default of material in the ceiling or roof affects not only its stability, strength and economy, but also the walls, columns and foundations— that is, the sustaining parts.

(107) The structure of a ceiling is based upon the principles of a bridge; that is, upon the principles of any sustained architectural member. Nature has given us two fundamental

forms of it: First, the suspended form; second, the arch form, or vault. A third form, nature gives us accidentally, that is, the *lintel*.

(108) If we analyze these three different generic forms of bridging, we will find that the first has a tendency to pull in the sustaining parts, and the second to push them out. The strength of both tendencies is equal. In the first the material works by tension, and in the second by pressure. For the first one, nature always uses fibrous material; for instance, as in the vine whose branches form a bridge which is suspended across a river. For the second, nature uses particles, connected together in cohesive work.

(109) These two opposite tendencies are united in the third form, which nature has also given to us; that is, the lintel, which is subjected at once to both tendencies. But, in the lintel, both tendencies are connected together, that is, the cohesive material which is working by pressure, and the fibrous material that is working by tension. Both thus form a united mass, and the result is that the part working by pressure, which is generally on top, is pressing (in virtue of its intimate connection) the other part that is working by tension, compelling to work by pressure that part which was designed

to work only by tension, which is generally at the bottom. . The result is that nearly the whole mass shown in the section of a lintel has a tendency to work practically by deflection. Now if to this inconvenience we add that no material has the same coefficient for compression as for tension, the difficulty of securing economy in a lintel or beam is serious, unless they are separated, and the two materials work free and independent of each other, in which case they will not lose any strength. That is the reason that no lintel or beam can be worked alone with economy. A lintel and beam united can be worked with economy when both materials are independent and free to work as is required. But this structure is not a lintel — is not a beam. It is just the combination that we gave in the beginning, that is, the suspended form whose tendency is to pull in the sustaining members or walls, working as tension, and the arch form whose tendency is to push out the sustaining members or walls, working by pressure. These two primal forms, when they are connected properly, give the most economical and easy ways to bridge. But in order that these compound bridge forms should work properly, they must have a very flat section, so that *all the fibres of* the rod may work practically by tension. One example of this application is a floor constructed with a continuous barrel arch (A), with some small bent rods (B), (Figs. 45 and 46), with a small partition laid over the rod B, rising to the barrel arch. This arrangement will form a continuous beam in which the barrel arch, and part of the partitions will work by pressure, while the rods will work by tension. The material in this position works with its true force.

(110) The rod can be calculated exactly, and independent of the section of the arch, and *vice versa*, with the additional feature that each material works at its best advantage, and the clay or arch is at the same time supporting the ceiling or roof, and forming a floor or roof, the economy

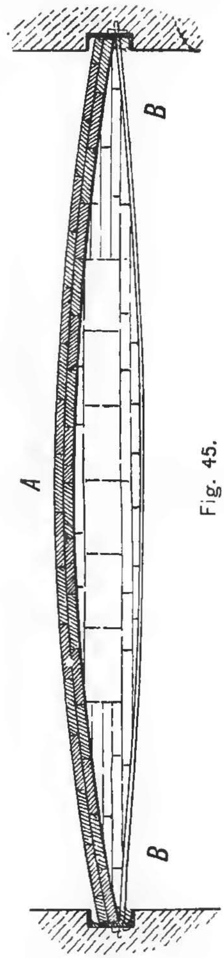

Fig. 45.

of which is evident. This is not the case with beams laid parallel next to each other, and wooden planks or brick arches, etc., between, in which the beams are the real support, and the wooden planks and brick arches are only for a bridge between, adding weight. Here the virtual beam or lintel is a continuous one.

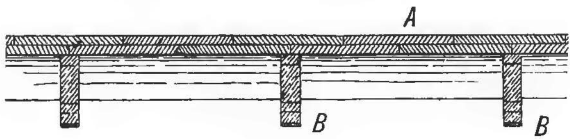

Fig. 46.

(111) For this reason, under the cohesive system of construction, if properly applied, the clay works by pressure, supporting itself, and the iron works only as a rod. If the system is not properly applied, or is misunderstood, no advantage can be obtained. This is the case when girders or beams and barrel arches are combined, as we have already stated. The arch is intended for bridging between girders, and the girders not only work by deflection or deadweight, which is the most unfavorable condition, but the barrel arch and the weights on it are added to that of the girder, and in consequence the clay does not contribute in the least to support any part of the floor, because it

depends on the girder. Consequently it must be heavy and expensive. Hence the construction shown in Fig. 45 will always be a superior, more economical and more rational construction.

(112) Better advantages must arise (see Figs. 47 and 48) when the rod is in a circular form, making a continuous rod, and the barrel arch is changed to the form of a dome. In that case we have the following advantages:

1. That the material which is working by pressure, namely, the clay, is not only working, as we stated in the theoretical part, by pressure, but also by tension, when the form of a dome is assumed.

2. One rod is enough, set just at the beginning of the dome in the form of a ring, B, B′, B″ (Figs. 47 and 48), and as the material itself is working by tension, counterbalancing in some part the pressure of the dome, this ring or circular rod can be of a smaller section than for any barrel arch of the same surface.

3. The circumstance that the rod is in the form of a ring, at the base of the dome, gives the great advantage that the iron is better situated to prevent its being heated in case of fire.

4. The form of the dome, which does not require any rod between the skewbacks, or springs

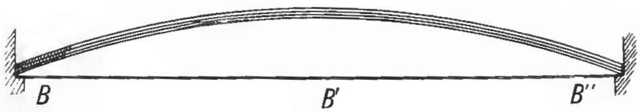

Fig. 47.

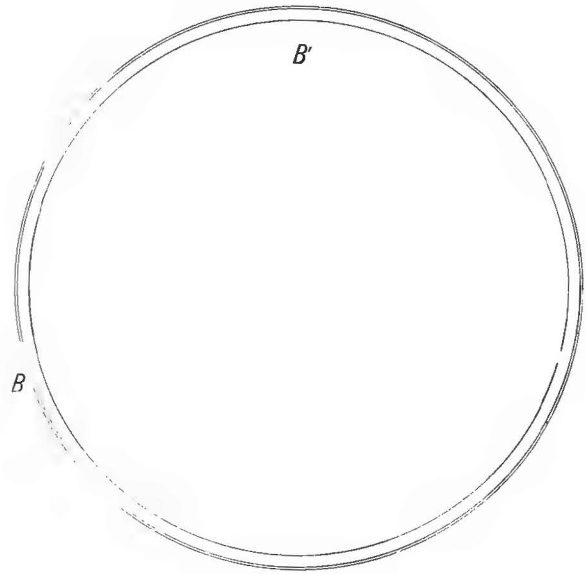

Fig. 48.

of the arches, leaves the dome free from any interference, presenting better finished work, and a noble surface for presenting decoration, being itself the principal member of the decoration, by its form if not by its material.

5. This continuous form of the dome, without any interference of rods, by its smooth, curved surfaces, affords also the best inside lines for any ceiling, from the point of view of hygiene and ventilation.

HOLLOW TIMBREL ARCHES FOR FLOORS AND ROOFS.

(113) In roofs, and also in ceilings where decoration is required, the single timbrel arch has the inconvenience that the roof transmits the temperature, and is cool in winter and very warm in summer; and in ceilings for decoration, if concrete is used for filling, the condensation of the interior atmosphere causes dampness in the ceiling, changing the colors and destroying the decorations. To avoid this it is necessary to build the ceiling and roof hollow, that is, composed of two series of timbrel arches, one on the underside, as a ceiling, adding another on top, as a floor or a roof, by means of a rib built between both timbrel arches. The ways to obtain these forms, which

we may term "tubular timbrel ceilings or roofs," are infinite. I would here refer to the following examples in this country: — The domed library ceiling of the Arion Club, 59th Street and Park Avenue; the floor of the extension to the Young Women's Christian Association's building over the boiler-room, on 16th Street, near Fifth Avenue, New York; the main staircase of the Public Library, Boston; the large ceiling of the driveway for the same building, and others.

(114) This hollow arch, or double arch with a separator, has not only an advantage over ribs as an insulator from dampness and heat, but it also increases the strength of the arch, as it adds to the strength of a tubular girder when the moment or radius of gyration is increased.

(115) For that reason, in any arch that requires more than four courses, it is better, if the space is not limited, to build always in a "tubular" way, that is, with two courses in the bottom, and ribs over as a separator of one, two, three or four inches, according to the space at our disposal, and two courses on top. Again, this "tubular" construction has the advantage that the section of the arch can be increased at will in the haunches, or at any place where the arches require thickness, thus increasing the

radius of gyration at a very small cost. Some floors can be built hollow by means of building two series of arches between the beams. One example of this is the parquet floor of the Carnegie Music Hall. The space between the two series of arches was for ventilation purposes, having two courses in the bottom, and three courses on top, between the girders.

HOLLOW COHESIVE WALLS.

(116) Although cohesive walls hardly belong to the subject of which we are treating, they are so connected with the construction of arches, on account of their being the support and forming part of the skewbacks of the arch, that they require some mention, especially hollow walls. The enormous thickness given to the walls of the present buildings of ten, twelve and more stories, does not seem justified by the present advancement in the character of material; but it is justified if we take into consideration that in these walls materials are generally used that require several months to set, not only because of the slow-setting nature of the mortar used, but also because it requires the presence of air for its transformation as an element for setting.

(117) With this kind of mortar, all the walls built with rapidity to a great height cannot be

guaranteed, because the mortar receives more weight than it can support without destroying its condition of setting. Why do we not build these tremendously high walls with Portland cement? As the strength of this material, when set, is similar to the brick, and as the Portland cement has the condition that it does not require to be exposed to the air for setting, the walls could then be built with rapidity without compromising the setting conditions of the mortar.

(118) It is true that in this case there is no necessity for a wall of such great thickness, and the radius of gyration for the wall can be reduced; but that gives the idea of building these walls hollow, that is, of giving to the wall the surface required for its strength, yet increasing the radius of gyration, by building the wall with a separation in the middle; which means, to make two walls connected together in order to give the same moment as in the thick wall mentioned above, but with less material. In this way we secure the valuable condition of isolating the inside wall from the outside, which is one of the most important problems of the modern science of construction.

We have now arrived at the conclusion that hollow walls are a necessity in modern buildings.

(119) Some remarks are necessary here in regard to these hollow walls. First, the full dimensions of the walls would be calculated in the same way as we are calculating now for any hollow bodies, and that is not only to justify the mechanical conditions of the wall, but also to give it the proper artistic effect. The hollow wall works exactly as a hollow column. If we take the superficial inches of any cast-iron column, of round or square section, and put all this mass of section solid, not only will the column be of less strength than in the other case when it is hollow, but we also find at a glance that its effect is meagre, poor and without any character. The same is the case in any wall. If we build any high wall without giving it the right mechanical dimensions, hollow or not, the effect will also be poor and it will be without character. Consequently these hollow walls would be regulated by the same principles that we have to apply to find the radius of gyration of any wall, giving to the hollow space the balance of the thickness necessary to the outside and inside walls, according to the coefficient of pressure of the material used for the same. In that way we secure, first, the exact quantity of material necessary as a support, according to the progress of the manu-

facture of constructive materials; second, we secure the same result of increasing the radius of gyration without increasing the cost of the wall, and the weight upon the foundation; and third, to have a hollow space always convenient as an isolater for other applications.

(120) Second, there is a hygienic advantage in the hollow walls, which secure absolute absence of dampness and condensation, thus making the building cooler in summer and warmer in winter. If the floors are also hollow, the hollow walls permit the building to be ventilated in the corners of the rooms where the impure air collects, and permit a greater section of ventilation than can be had in any other system without affecting the solidity of the building. A source of great annoyance to architects when a building requires a great number of flues, is that they have difficulty in finding places on which to lay the beams, making headers after headers, sometimes resting half a door against the head of a single beam. The brain of the architect is thus continually racked to make suitable framing plans. But if all the walls and floors are tubular, every part of the room can be well ventilated in every direction.*

* Although this is outside of our object, it may be remarked that these tubular walls and tubular ceilings also facilitate the

FACTORIES.

(121) There is a country which, like New England, breathes an industrial activity in cottons, woollens, silks, laces, etc.; a country which, not only because it supplies its own market, but because of its export trade, more especially to South America, East India and North America, is known as the "Spanish Manchester." I refer to Barcelona (Catalonia, Spain), a country where I had for fifteen years my circle of operations as architect and specialist in this kind of building. Hence I can say, without ostentation, that I am not talking about that which is new to me. All that I shall do is to explain what has been done in the last twenty or twenty-five years. The Catalonians now have nearly seventy-five per cent. of their industrial buildings fire-proof.

How was this done? Was it because these industries were backed by larger capital, and

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establishing of a system of pipes, to connect every corner of the room with the fire-box or grate of the boiler-fires, ranges or furnaces, in order to burn the air, passing it through the flames, which is a good way to transform impure air. Such an appliance as this can be used for the ventilation of college buildings, and those who are further interested in this matter may be referred to plans and treatises sent by the author to the Philadelphia Centennial, on "Improving the Healthfulness of Industrial Towns," for which a certificate of award was granted, signed by your distinguished fellow-citizen, General Walker, as Chief of the Bureau of Award.

had better facilities, or made more profits than those of America? What is the reason that the Catalonian manufacturers have ceased making other than fire-proof buildings? Why do not the American manufacturers do the same? These questions I wish to analyze and answer.

(122) As far back as 1865 it may be said that neither in Barcelona nor in the provinces of Catalonia was there a single factory that was not entirely constructed, as here, of wooden floors, and most of them with wooden columns and girders; they also had, to some extent, the "slow-burning" construction — a combination of wood and iron. I remember when all the factories in the streets of Amalia, Rierretta, Luna, and the districts of San Pablo and San Pedro, were of wood. So old and so saturated with oil were these buildings, that the smell arising from them was ominous of immediate danger, perhaps caused by the knowledge of the scene of horror which would ensue should there be the least neglect, by fire. Nearly all of these buildings have disappeared. Their owners, with wise judgment, have built their factories less closely together and on another system, better suited to their interest — that is, of fire-proof construction.

(123) Some may imagine that the manufacturers of these places were richer or safer in their investments, thus requiring more permanent and safer buildings; but this is not so, as they are afforded very little protection, their markets being almost open to the French and English manufacturers, and any slight change of the tariff threatens immediate danger. What was the cause of this change?

(124) These manufacturers had learned from experience, that, notwithstanding the insurance money paid, in case of fire, the factory must be stopped for a period, and that customers, if not supplied, will go to some competing firm; so that, when they get started, they practically begin anew. *They also know that the wear and tear and depreciation in a wooden building in five years equals the extra cost of a fire-proof one.* A factory costing $20,000, requiring to be rebuilt in twenty years, means that five per cent. per annum must be laid away to restore it from time to time. This means that in five years the factory costs $25,000, or as much as a fire-proof one. All these considerations, and the increasing exigencies of the fire insurance companies rendering them more careful in the issuing of policies, compelled the manufacturers to open their eyes to the value

of fire-proofing; and under these pressing necessities some of them decided to build their factories fire-proof.

(125) But twenty-five years ago the Catalonian manufacturers were in the same position as those here. They knew only of the English fire-proof factories of iron and small brick arches, expensive and not fire-proof, with the difficulties connected with this system regarding the running of shafting, in which any of the frequent alterations required in every factory is an enormous task. Realizing this inconvenience, the manufacturers of Catalonia did not at a single bound go from one extreme to the other — that is, from the poorest to the most expensive; they took precautions so that the sudden change might not ruin them, and commenced to study the way to overcome the inconveniences of the English system of fire-proof industrial buildings, and find such a system as was fitted for the manufacturers' convenience, and avoid the heavy losses through stoppage, which the insurance companies could not pay them. No one can blame this prudence, for the capital invested in the factory is the manufacturers' tools, like the hammer and chisel in the hands of the workman; they cannot, they must not, employ more than just what is necessary, with

the least chance of loss. And because of their prudence they now have, as I said, more than seventy-five per cent. of their buildings really fire-proof.

(126) This system of fire-proofing was a combination of clay and wood or clay and iron, with ten feet six inches or more span, according to the bays. I must remark that, for every ten fire-proof factories, eight were constructed of clay and wood, and two of clay and iron. The adopting of this combination of wood and clay, in preference to iron and clay, was not so much due to economy as to the belief that in the way applied it was more fire-proof, besides being more adaptable and convenient for changes and alterations, reducing wood, however, to the lowest quantity, and putting it under absolutely safe conditions. One of these was the firm of Batllo Bros., for whom I drew the first factory plans in this way in Sarria. This was so eminently successful that several others were at once erected on the same principle.

Now, if these men had not been prudent in this matter, and, instead of making this combination had been extravagant in adopting the heavy iron and heavy clay as in the English system, they would have secured improvements in name, but not in fact; for cash is the key to the situation, and, although the manufacturer has noble aspirations for progress and improvement, he knows that he must maintain prudential limits. I have enlarged on this point, on account of its importance.

(127) Thus was established in Catalonia two systems of fire-proof factories: the one type shown in the factory of Vidal Hijos, constructed in 1871; the spindle building of Batllo Bros., in 1869, and several others; the other tpye shown in the loom-room of Batllo Bros., the woollen factory of Carreras, etc. The first type consists of wooden girders and tile arches, and the second of tile arches for ribs, with small iron beams with dome between. (See Plates 1 and 2, at the end of this book.)

(128) What is the combination — iron and clay, or wood and clay? It is very simple, it is only iron or wooden girders, set apart over columns at the regular distance of a factory bay, ten feet six inches or more, as has been stated, and between them tile arches, similar to those now to be seen in the Boston Public Library, or the Harcourt Building, or Exeter Chambers, in the same city.

(129) The combination with iron can be executed in two ways, as it is used in some of the rooms of the library, acting as a beam or girder,

working by deflection; or, as used in the Colorado Telephone Company's Building, Denver, and the Young Women's Christian Association Building, New York, working principally by tension. This latter form may also be seen in some of the rooms of the Boston Library. When the combination is of wood, it is working in deflection, as in the case of iron, and in some cases by tension. The construction is cheapest in both materials when working by tension.

(130) Some may think that fire-proofing in Catalonia is cheaper than here. This, in a general sense, is not so; because, had they accepted the English system, the relation between the English system and the cohesive system would have been the same there as here. It may be supposed that the cohesive system is dearer here than there. I will show wherein the difference lies. It cannot be in labor, as the same proportion of difference exists in the wages of carpenters for wooden construction as for masons; and, as the walls are the same in either case, the difference is only in the floors; and, if any there be, it must be in the material. Wood costs the same there as here. Portland cement, one of the main factors in the construction, costs three dollars a barrel in Spain, against

two and one-half dollars here. Plaster costs about the same. The difference is only in the cost of the tile, which in Spain can be purchased at five dollars per thousand, while costing fifteen dollars here; but taking into consideration the fact that in Spain they use tile five-eighths ot an inch in thickness and here one inch, and that the tile is only one of the components, and that it is only in this special material that the cost is greater, the real difference in the price per foot of that material is only twenty-five per cent. This twenty-five per cent. difference in the cost of tile cannot be sufficient reason for not using the same construction here; for, in a factory one hundred by one hundred feet, or ten thousand feet square, the difference in the floors would only be eight hundred dollars. I do not think this eight hundred dollars would prove an insurmountable obstacle to a New England manufacturer; therefore increased cost cannot be the cause. In the iron there is a little disproportion; but, as the economic state of a country is relative in all things, if the iron and construction are cheaper, the production is also cheaper and the income and interest less, so that does not effect the comparison. Consequently, the difference in cost there and here between the wooden and fire-proof factories is really the same, and the reason for not adopting the same system here is not due to the extra cost of eight hundred dollars for each ten thousand feet of floor.

(131) The Cohesive System is the most profitable for factories, for the following reasons:

(132) 1. Rigidity in the floors, representing an economy in coal: It is evident that all oscillating movement in the floor is a loss of power that represents at the end of the year a sum of coal consumed in excess. In the walls and floors of my system the rigidity is absolute, and in a building of great surface, that represents, as I have found by experiments with the old and new factories of Muntadas, in San Martin, before referred to, a net saving of between five and six per cent.

(133) 2. It is common to see in wooden floors a warping of the wood, caused by the change of temperature or humidity, or currents of air or the proximity of heated bodies, thus changing the level; consequently the machinery is thrown out of level. Then ensues a loss of power, if they are not re-levelled; and when this is done, there is no certainty as to their stability, as another change is imminent. The same is true when, in consequence of the bad

setting of the beam, caused by no ventilation in the end, dry-rot is precipitated, the more so if care has not been taken in the use of the lime. Very frequently the beams have to be replaced. In my system all the material is permanent, like solid walls.

(134) 3. We know the necessity for the use of grease and oil in factories, and the dangers incident thereto, especially in cotton mills, because of their extreme inflammability; and, as all manufacturers require great room surface, and as the distance of many parts of rooms is far from the exits in these buildings, there is a constant menace to safety.

(135) In factories constructed on the Cohesive System, the floors being laid with tiles, nothing is affected by the oil. The cotton, if it takes fire, has nothing to burn; no iron work is exposed; all is clay or cement. (See Figures 49, 50, 51, 52, 53, 54, 55, Plate No. 1.)

NOTE.— The walls are constructed of clay tiles, the piers being built hollow and utilized as ventilating-flues. The beams are all covered in the arches and work under tension.

Hard-burned clay tile floors, etc., are used, as well as fire-proof columns; no iron is exposed.

There are on each floor, in addition to space appropriated for manufacturing purposes, offices, store or sample rooms, toilet-rooms and fire-proof stairs. The building is well lighted and ventilated, and is adapted for almost any kind of manufact-

STORES AND WAREHOUSES AND COLD STORAGE.

(136) As these buildings require very strong floors, barrel-arch bridges must be constructed, two feet apart, built to the level of the crown of the arch. These bridges must be of the same material as the arch, and built, if possible, at the same time as the arch. The bridges must be in and against the next haunch of the opposite barrel resting against the wall; if not, they need a rod on top to tie both ends. The dome is most desirable for this class of buildings, having the highest strength with the smallest section. The bridges in the dome must be radial, but connected with some rings. The rings must be as high as the ribs.

DWELLING-HOUSES.

(137) It is universally believed that the object of fire-proofing in private houses is to guar-

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ure. The stories are 14′, 13′, 12′ and 14′, respectively, with bays 25′ x 106′.

The safe load is 150 pounds per square foot, one month after built; 350 pounds six months after built.

The building is four stories high, 238 ft. deep and 134 ft. wide, making 26,000 square feet, and the price is based on nothing smaller.

The cost is 89 cents per superficial foot for each floor, including walls, floor and iron construction, against 75 or 80 cents per superficial foot of wood floor and girders and walls.

antee only against fire, when in fact its main value, which no insurance can protect, is to give a perfectly air-tight floor and partitions between the apartments in any dwelling. With wooden construction, it is practically impossible to avoid cracks in the ceiling and walls and a separation in the joints of the wooden floor; and, in consequence of this, each floor is in communication with the floor below or the adjoining room. This is true in any kind of building with wood, and if it is dangerous to have the air passing between two different apartments, it is also dangerous to have it pass between members of the same family. Medical science has settled that isolation is absolutely necessary in some of the ordinary diseases, to prevent their spreading.

(138) There is frequently seen in large cities (perhaps compelled by local law), in apartment houses, a notice on the door, that some disease exists within; in order, perhaps, to prevent the intrusion of callers. But that does not prevent communication through cracks in the floors and partitions. One can often see, through a crack, a light in a room below or adjoining. This crack allows of a circulation of the infected air to the several families of the house. These facts speak for themselves. This circulation

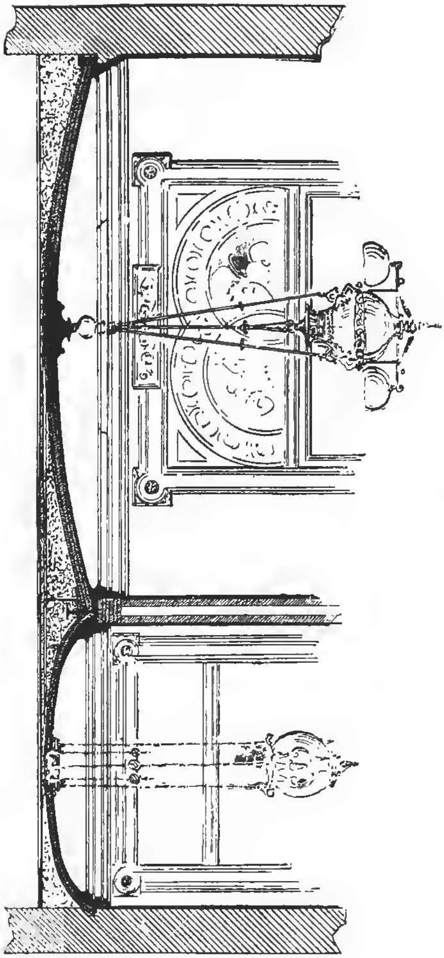

Fig. 56.

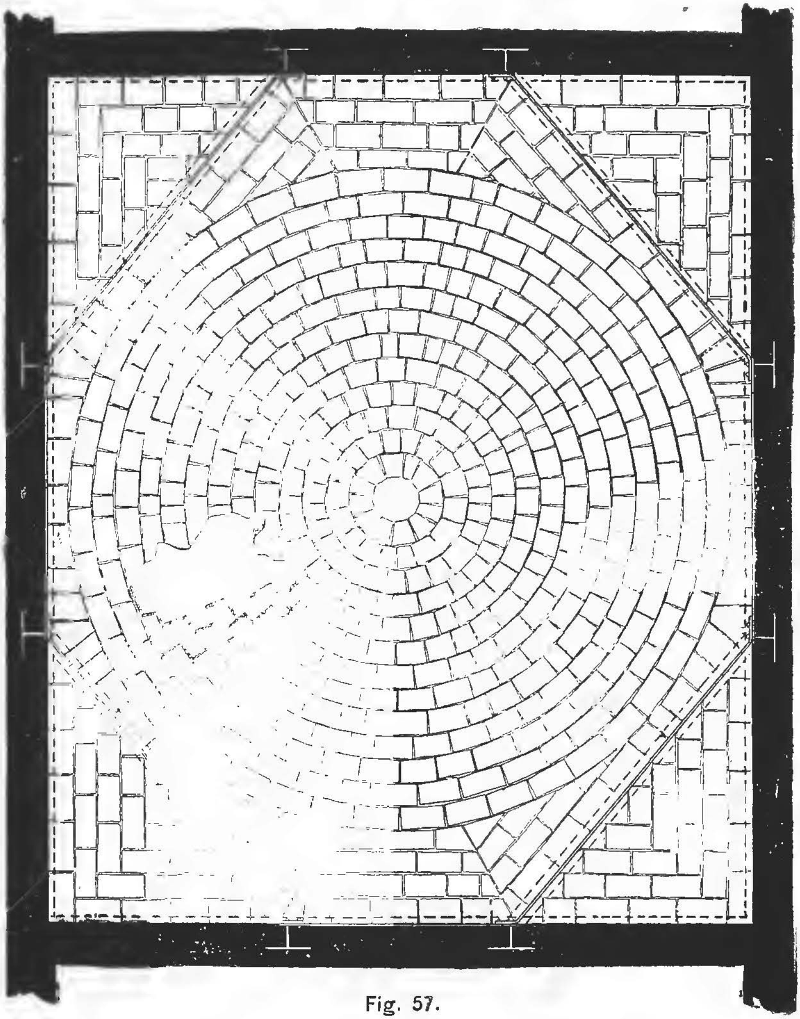

Fig. 57.

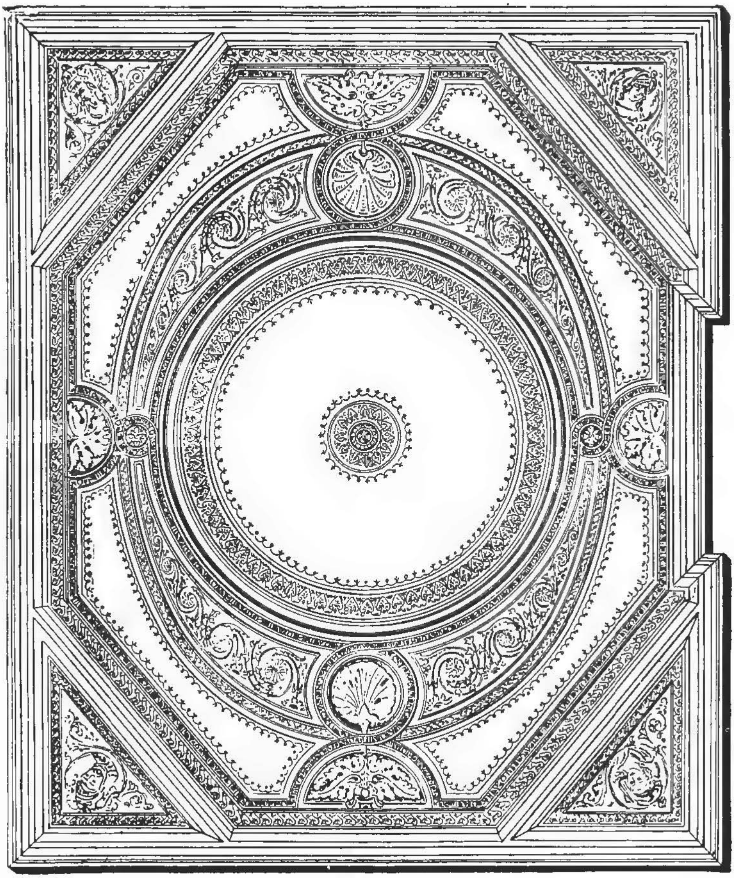

Fig. 58.

through the walls and floors cannot be prevented if wood is used, as every one knows that the natural movement of the beams cracks the cornices and ceilings; and afterwards, when the floor dries, the joints open.

(139) With the complications we have to-day in ordinary dwellings with steam, water and gas pipes, not to speak of electric wires, which cannot be fitted tightly, the danger of leakage is increased.

The Figure No. 56 represents the section of a dwelling-house, showing a hall entrance and parlor. Figure 57 represents the framing iron necessary for a dome for such a parlor and the rough tile con-

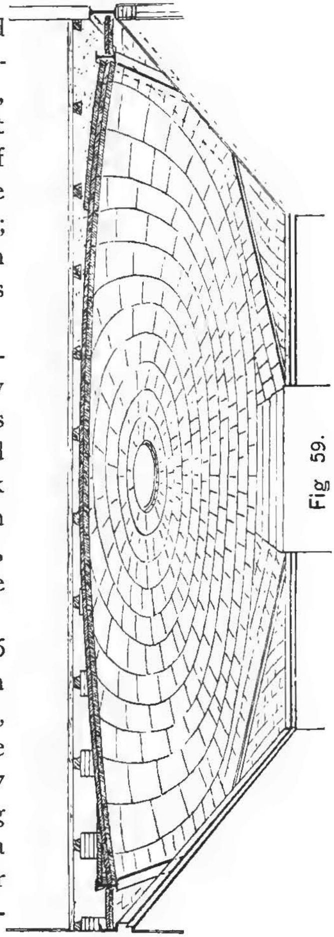

Fig 59.

struction before being decorated; and Figure 58 shows this construction decorated. Figure 59 is the section of ceiling-floor. The section shows two cases: first, one-half the drawing shows the floor filled up level with concrete; second, on the other side the concrete is left out in order to leave it hollow, and the sleepers are supported and fastened with small anchors with tile piers laid over the arch.

(140) We recommend the use of domes in private houses. First, because they are stronger than barrel arches, and cheaper; second, because they are of better decorative form.

(141) To accomplish the object of isolation, coincident with adequate strength, it is sufficient to have only two courses of tiles, each one inch thick, for domes from sixteen to twenty feet span, introducing, in some cases, ribs for extra strength.

COTTAGES.

(142) One of the frequent demands, especially in New England, is for fire-proof cottages. Some ask for the cellar only to be fire-proof. The fire-proof cottage must be very economical.

(143) To make the entire construction of the cottage fire-proof the dome is the cheapest and most appropriate method.

(144) All the partitions may be constructed with clay blocks, the advantage of which is that they can always be utilized. These clay partitions need cemented door-way frames and window frames, practically requiring only wood for the movable parts in the doors and windows. The roof of the cottage can be of tiles, glazed or salt-glazed, laid with Portland cement. The outside walls may be built with large blocks of tiles with air-spaces between.

HOSPITALS AND SCHOOLS.

(145) In hospitals and schools the ceiling could be composed of two parts, the ceiling and the floor, with an air cavity between in such a way that ventilation for the floor above and ceiling below should be sufficiently distributed, in order to have the greatest number of registers and ventilation pipes extend to every corner of the rooms. This condition requires that the spaces between the floor and ceiling be free, for which very small beams are required. Domes in schools and hospitals are the best, because the beams may be small enough to work only by tension.

(146) Barrel arches are not so convenient, because the skewbacks always intercept communication with the next arch, and when a flat ceiling is built under the barrel, the ventilation

can only be done longitudinally without expense and without weakening the arch.

OFFICE BUILDINGS.

(147) The introduction of a great number of stories in modern structures suggested to architects the use of very thin floors, in order to gain in height, and also in lightness. The use of domes, well combined, has great advantages in this connection.

STAIRCASES.

(148) One of the most valuable applications of the timbrel arch is the staircase constructed under our system (Plate III).

The materials which are in general use today for staircases are wood, iron and stone. The first one is not fire-proof. The second is hardly fire-proof, and neither of the first two possesses sufficient architectural character. The stone is good, but it is too heavy and expensive for dwellings and other similar buildings.

(149) The advantages of the timbrel arch in the staircase are as follows: —

1. It is absolutely fire-proof.

2. It is adaptable to any size and in any place where two walls can be disposed of, or one wall and two floors.

3. It is a constructive arch and is susceptible of any decoration, and gives infinite richness without great expenditure. Two kinds of staircases can be built on this system. One may be called a stair of surmounted arches, and the other a spiral staircase. But when we say spiral staircase it does not only apply to a circular base, but also to a rectangular base.

(150) The first one, as the name indicates, is a series of catenarian arches, built, one over the other, in an angular way. The second one is a continuous arch from top to bottom without any intersection except in the walls.

(151) The way to trace both of these stairs requires some knowledge of the manner in which they work, and it is difficult to explain how to determine the right form of the arch of any of these stairs, and to establish any definite principles for every case, because the problems change to infinity. The combination of the spring of the arch with the continuous curve needed under the platform in order to adjust the adjoining flight is a question of mechanical appreciation, because it is necessary to take into consideration the space required for the steps, and to give the right continuous curve of pressure to the arch. For this reason no precise rules can be given.

(152) Nevertheless, one of the principal rules is that the first step must be in the lower spring of the arch, which is at the beginning of the flight, and if any flight is longer than the steps required the platform should be placed at the head of the flight, instead of at the beginning. These principles are necessary in order to avoid the results of using brackets, which destroy the character and weaken the stairs.

(153) Another principle is that the cross-section of any flight is in the form of a bracket; that is, the arch for the surmounted stairs is formed by two catenarias, one lower, at the intersection of the wall, and another higher, at the outside of the steps, under the banister; and to determine the difference between the two catenarias is a question of appreciation in view of width and the length of the flight, and the length of the adjoining flight.

(154) The form of bracket for a spiral staircase must be determined by the two spiral lines, one lower than the other, the lower one being against the wall, and the other against the banister on the end of the steps.

(155) The problems of staircases built with timbrel arches are complex and varied, and would require a special treatise.

(156) The stairs that may be referred to are: the main stairs of the Boston Public Library; the stairs for the American Legion of Honor Building, Huntington Avenue, Boston; the stairs in Exeter Chambers, Boston; the stairs for the private residence No. 122 West 78th Street; four private residences at 154, 156, 158 and 160 West 82d Street; the apartments of 99th and 100th Street (see Plate III), corner of Columbus Avenue, New York; and the spiral stairs in the Washington Memorial Arch, New York.

BRIDGES.

(157) Among the applications of the timbrel or cohesive arch one of the most valuable is the masonry bridge built on these principles.

The costly wooden centres required for masonry bridges, built either of brick, concrete or stone, cannot be avoided in order to have the centre rigid enough to receive the weight of the masonry, so as to give to the material rest for a good setting. This takes a great part of the estimate for any bridge, particularly if the spans are large, as is the case in all good bridges.

(158) In timbrel arches the estimate for the centering is a very small matter, the reason for which is easily understood. As the principle

of Cohesive Construction with tiles is to build the arches by coats, one over the other, with broken joints, each coat makes a centre for the next; so the centre can be considered only for the first few courses, whose weight is very light. This advantage permits of larger spans, gives better conditions for the absolute setting of the material, and is economical. But these advantages, already mentioned, are not the only ones which this system possesses for bridges.

(159) 1. In the cohesive-tile system the bending-moment in any section can be increased without adding material, by making the section tubular.

2. The railing can be constructed in connection with the bridge under such conditions that the railing can be counted as one of the members which give strength to the bridge.

3. The tubular condition, as well as the construction of the railing in connection with the bridge, solves in a favorable way the stability of the bridge in regard to moving loads.

(160) Figures 60, 61, 62, Plate IV, is a plan and section of a bridge. It is not altogether tubular, but only at the ends, as can be seen; the bending-moment increases at the ends, in order that the course of pressure can be inside for moving loads.

These ends are formed by two series of arches. The arch underneath is a continuous dome decreasing the radius of its spheric surface at the ends, and over the dome, the second arch (segmental) pursuing just the lines of the roadbed, connecting both arches by ribs.

In a separate book we hope to treat more extensively on this specialty of bridges.

CRITICISMS OF THE COHESIVE SYSTEM.

(161) Many discussions have arisen, both in favor of and against the Cohesive System in the past year, as is natural when any new application is brought forward in the arena of scientific discussion. But it has occurred that the greatest friends of the system sometimes go too far in their enthusiasm and favor of the new idea, the result being that in their hands it is disfigured or erroneous. For instance, it is said:—

(162) 1. That the arches under this system have no thrust. It is and it is not so, as I will explain later.

(163) 2. It is said that the system is more expensive than any other system of fire-proofing, or that there is no economy in it. To this I will answer, that it depends on the way it is adapted.

(164) 3. That the ceilings of this construction require greater height than others. Consequently, it is necessary to build every room with high ceilings, and that, of course, causes the building to be higher. This impression probably exists because some people may have seen some arches or ceilings that have been constructed specially with a high rise, to give more character or to show more constructive lines; and they imagine that all ceilings must have a similar rise, when the truth is, that on an average they take less room; but this depends on the wishes of the architect who is applying the system.

NOTE TO THE READER.—Another consideration has arisen in discussion, which I will ask permission of the reader to let me answer; that is, the question in regard to the patents. Now, if the system is patentable, in what does the patent consist, and by what is the patent warranted? In the first place, I must say that, allowing that in a small portion of Spain and Italy a similar system was applied empirically, and on a smaller scale, it is a fact that it is not applied in any modern public building in either place, because, as I say, it has only an empirical application; nor has any academy a regular system or scientific method for the application of it.

Improvements have been introduced constantly. Some of them are as follows:—

1. The custom was to use plaster in the first and second courses; and it was not possible to construct in any other way. This gave an excess of plaster, which was very prejudicial, as all intelligent builders know, and of which we give

(165) In answer to the first I will say that the thrust depends on the form and not on the material, as stated before. (See page 75 in regard to barrel arch and domes.)

(166) The answer to the statement that it is so expensive that it cannot be used with economy, is as follows:—

(167) 1. As we have said before, the barrel arch has some thrust, and requires something to counterbalance this, that is, a rod, or rods. That is one of the causes which makes the barrel construction more expensive than the dome.

(168) 2. The barrel arch requires two sides for the arch to rest on, such as girders or beams,

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full explanations in this book. I pursued this method for several years, with all the attending inconveniences, trying to discover a means of avoiding it. To-day we are using one-tenth of the plaster we used originally.

2. Before, it frequently happened that, because of the negligence of workmen or others in stepping over or putting heavy weights on the arch before it had set, or for any other cause, some of the tiles of the first course, having become a little separated, were likely to fall. To-day, by means of a flange, the tiles, if any become separated, can never fall, and none the less have the same stability.

3. Formerly the tiles used to be covered by plaster, leaving that as a rustic form of rough material, purely constructive; to-day they are employed in a more useful way, the tiles forming the construction and decoration. That was one of the constant and noble aspirations of the art of construction; but to arrive at this point with the tile was not an easy problem,

or walls. These girders or beams must have the strength to support all the weight that the arch carries, besides the weight of the arch. The prices of the girders or beams must be added to the price of the arch. Consequently we have the same objection as in the regular fire-proofing process, where the arches also rest against the beams, the advantage being that our barrel arches are lighter, and the span can be greater; consequently these girders or beams can be lighter and cheaper. But, nevertheless, the fact remains that we must have the girders or beams, and the value of these must be added to the arch. The result is, if we have an economy

because the decorative tile is the first course, which is the most difficult to have nicely and properly jointed, while the material required for this first course gives no chance for carefully made right angles and even joints.

4. In several cases, for industrial, mercantile or special buildings, it is necessary to have flat ceilings, and very light floors, practically deafened. We have these conditions provided for to-day in the cohesive system.

Now, if the object of the law of patents is to guarantee the intellectual work applied to new applications and improvements, is it possible to have no guarantee for all our new applications. But the protection of patent law was invoked, not with a desire of making a monopoly, nor for gain only, with that object. I may remark that, notwithstanding to some architects the system is acceptable, the truth is that the day is very far distant when it can be given to the common use and free practice of all kinds of contractors, while they have not over the ordinary fire-proofing, the barrel arches cannot compete with slow burning construction, in consequence of the heavy girders required.

(169) 3. But if, instead of using the barrel arches on the Cohesive System, we use the domes on the same system, we have economy, if properly applied, because we have not the objections named—that is, the use of heavy rods between heavy girders, and the use of girders or beams themselves.

(170) Now, suppose we receive a plan from an architect, as is generally the case, with barrel arches and girders, and we quote a price which is more expensive than the combination of the

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yet at their disposal the elements necessary, neither of material nor expert hands; and for this reason the system would be dead, if it was not restricted. For instance, suppose an architect, knowing and believing in the system and convinced of its utility, as there are many to-day, should project a building under this system, as insignificant as it is or appears to be. If he called for competitive estimates, in order to obtain the price, I am sure that neither the architect nor the owner would be certain that the contractor was practically able to erect the building with success in the construction. The architect, not having enough confidence in the contractor, not knowing whether he was practical or not, and realizing that he personally is directly responsible, knows that he will be a slave of the building. On the other hand, the owner, knowing that the system is new and put in the hands of a contractor who cannot give references as to his knowledge of the matter, by his past record, would not have confidence in him, and would pay his dome without the heavy girders and heavy rods. The result is, that it is not as cheap as other combinations that we have already built and are now building. Is it the fault of the system? Most certainly not. The fault is, that it is not well applied.

I must remark with great satisfaction that we have commenced to receive plans from architects in every part of the country, some of them showing that this system is commencing to be well understood and appreciated at its just value.

(171) In regard to the question of height, I can say that, notwithstanding we give ten per cent. rise, as a rule, on all of the arches, it does not mean that it cannot be less or greater; just as, in the ordinary system of beams, we know that the higher the section we give to beams the more economical is the result. For instance, if in a floor framing of beams twenty-five feet in span

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money without a guarantee that the contract was well and safely performed. The contractor, too, would not be in any better position: he could not find the material nor the workmen, under the ordinary conditions that other systems would allow, and consequently everything would be against either success or economy.

This is the reason that it was necessary to accumulate, year by year, elements of security for architects and owners, and acquire elements for supplying the market with material and expert hands, educating able foremen, able masons, and able we use beams eight per cent. of the span, the ceiling would be cheaper than if we give five per cent. for an equal load; for, in the first case, with less pounds of iron, we have the same resistance. The same is the fact in the arches and domes; the more rise we give, the more economical they are. This means that we use the same rules as in general bridging; that we can reduce the rise to eight per cent. in ordinary construction; and, as the arch's form gives opportunity for greater height to the ceiling in the centre, the result is that practically the ceilings are higher in our system than in any other system, taking only, in the crown, six inches of room, but descending on the side, and occupying the place of small corners in all the regular ceilings. Consequently, I cannot see in what way this system takes up more room than any other.

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helpers. The reader will appreciate the cost, the great sacrifices and the capital expended in order to succeed in all this, besides the necessity of placing the system on a scientific basis. All of this could not be done without a patent guaranty; and all of this had to be perfected at the commencement of the first year's work, because it was a labor of propagation and evolution.

It can be seen with these explanations that it was necessary to protect the system, not with a desire of making a monopoly for gain only, but to assure its success.

MATERIALS AND IMPROVEMENTS IN THE FUTURE.

(172) My intention is not to uphold the use of concrete in construction where cohesive strength is required, because it is a slow process. It works practically only by pressure, and there is no shearing strength in the joints, or a chance for perfect setting. It makes a heavy load, especially on the centres during construction. It produces a great load of dampness in the building, and is ruinous for patching or alteration. After several years' experience in concrete construction with no satisfactory results, I have come to the conclusion that the tubular system, as applied in constructing walls and ceilings built with light and well-burned clay, and good Portland cement, is the best, safest, most substantial, economical and most rapid method of construction, on the Cohesive System, for dwellings and other kinds of buildings.

(173) By light and well-burned clay, I mean such as was used by the ancients, which, although as strong as the others (from 1,500 to 2,500 pounds per square inch), has an average weight of from 80 to 120.16 per cubic foot.

(174) The mortars used must be of the quality called Hydraulic — mortars that do not need exposure to the air for setting, which, for our especial work, is Portland cement.

(175) The bricks must be of as large dimensions as a man can easily handle, and of such weight that a man can work with them all day. These conditions produce a brick about four pounds in weight (when the ordinary clay is used), and about an inch thick, and seventy-two square inches in surface, or $6'' \times 12''$. These tiles must be a little porous in order to absorb some of the excess of water in the cement. It may be added that the breaking load for a square inch of tile is between two and three thousand pounds.

(176) It may be remarked that a great deal has still to be accomplished by way of improvement, and it is necessary to call for assistance in perfecting our knowledge of the art of building, especially from manufacturers of materials and architects.

There are three improvements that may be suggested: —

(177) 1. The technical part ought to be put in a treatise, in order that it may be used in the schools of technology for the benefit of the constructive art.

(178) 2. (This to manufacturers): Our tiles as well as our bricks are too heavy. The cupola of St. Sophia has some rings that were built with lava (pumice stone), and some with brick so light that it would float in water. We have

some of this kind of clay in Spain (Barcelona and Valencia; also in Alcora, north of Valencia). Perhaps the people working in the old mines between Peniscola (Valencia) used this kind of clay, but investigations on my part have failed to discover it. The idea of looking for it in the mining districts led me to make a search for it in Colorado, with flattering prospects. I have a specimen from Colorado, but it is heavy; we are using lighter tiles for ceilings.

(179) The West is much advanced in the preparation of fire-clay, though not as much as in Spain; and in some parts of Mexico they are better prepared than here in the East for ceramic work applied for architectural purposes, and they have given some attention to the lighter brick.

(180) It is an error to believe that the heavy brick is the best; the light brick, which I mentioned, has a breaking strain of 2,200 pounds, and will float in water.

ECONOMY IN THE FUTURE.

(181) The clay in the tile we use is about the same as that in the common brick, and the volume is about the same, from 4, 4½ to 5 pounds. Our tile is 1 x 6 x 12 inches, or 72 cubic inches, and the brick is 2¼ x 4¼ x 8, or 72 cubic inches; but we have to pay from $18 to $20 per thou-

sand for the tile,* while brick costs from $7 to $9 per thousand.

(182) When we consider that tiles are made in blocks of six tiles each, and thus more easily handled than brick at the factory; that they are thinner, thus drying more rapidly and being easier burned with less fire — it would seem that they ought to be made more cheaply than brick; and such is the case in Spain, where brick costs from $6 to $7 per thousand, and tiles from $4 to $5 per thousand.

(183) This anomaly is perhaps due to the fact that as yet there has not been sufficient demand for these tiles here to cheapen their manufacture by producing them in large quantities.

(184) In regard to cement, we now have to pay English manufacturers a large contribution on the Portland cement we use; when it can safely be made in this country I suppose it ought to be about twenty per cent. cheaper. We ought from these two sources alone to be able to cheapen construction from twenty to thirty per cent.

(185) 3. (This to architects): In concluding permit me to put before you the following thoughts, which are not my own, but those of one of the eminent English authors of the first part of the century: —

* The cost now is from $10 to $12.

(186) "What is the best type of structure — that which for equal periods of duration has more per cent. of its full-covered area occupied by solid walls, or that which has less of its surface so occupied by walls?

"In the contemplation of buildings which show their strength by their age, the comparative science displayed may be partly estimated by an inverse ratio of the mass of materials to the space covered.

"The following list of notable buildings, with the per cent. between the areas covered and the wall surface, may be interesting: —

"The superficial feet of walls of the Church of the Invalides, at Paris, two-sevenths of the whole is solid.

"In St. Peter's, of Rome, one-fourth.

"In St. Paul's, of London, two-ninths.

"The Pantheon, one-fourth.

"St. Geneviève, at Paris, one-seventh.

"Salisbury Cathedral, one-fifth.

"Temple of Peace, one-seventh.

"Parthenon, two-elevenths.

"St. Sophia, cohesive system, one-eighth.

"A great building with few materials, besides the periodical approbation that it will receive from the age, will have an indisputable superiority as a rule."

TABLE OF THEORETICAL STRESSES FOR ARCHES 10% RISE WITH UNIFORM LOAD (W) PER SQ. FT.

Span in Feet.	Rise in Inches.	Thickness in Inches.	Area of Sec., 12 in. wide.	I of Section, 12 inches wide.	Bending-moment at crown. Inch pounds = W ×	Stress due to bending-moment = W ×	Thrust at crown = W ×	Stress due to thrust at crown = W ×	Thrust at springing = W ×	Stress due to thrust at springing = W ×	Maximum stress at crown = W ×
5	6	2	24	8	.540	.0675	6.16	.25667	6.673	.278	.32417
5	6	3	36	27	.540	.03	6.16	.17111	6.673	.18536	.20111
6	7.2	3	36	27	.7776	.0432	7.392	.20533	8.008	.2227	.24853
7	8.4	3	36	27	1.0854	.0588	8.624	.23956	9.3425	.2595	.29836
8	9.6	3	36	27	1.3824	.0768	9.856	.27378	10.677	.2966	.34458
9	10.8	3	36	27	1.7496	.09719	11.088	.30800	12.013	.3372	.40518
10	12.0	3	36	27	2.16	.12	12.320	.34222	13.346	.3707	.46222
11	13.2	3	36	27	2.6136	.1452	13 552	.37644	14.598	.4055	.52164
12	14.4	3	36	27	3.1104	.1728	14.784	.41067	16.016	.4449	.58347
12	1.44	4	48	64	3.1104	.0972	14.784	.308	16.016	.3337	.4052
13	1.56	4	48	64	3.6504	.1140	16.016	.33367	17.351	.3615	.44767
14	16.8	4	48	64	4.2336	.1323	17.248	.35933	18.685	.3768	.49163
15	18.0	4	48	64	4.860	.15187	18.480	.38500	20.02	.4171	.53687
16	19.2	4	48	64	5.5296	.1728	19.712	.41067	21.355	.4449	.58347
16	19.2	5	60	125	5.5296	.1106	19.712	.32853	21.355	.3559	.43913
17	20.4	5	60	125	6.424	.1285	20.944	.34907	22.689	.3781	.47757
18	21.6	5	60	125	6.9884	.13977	22.170	.36960	24.024	.4004	.50937
19	22.8	5	60	125	7.7976	.15595	23.408	.39013	25.359	.4225	.54608
20	24.6	5	60	125	8.64	.1728	24.64	.41067	26.693	.4449	.58347
20	24.0	6	72	216	8.64	.12	24.64	.34222	26.693	.3707	.46222
21	25.2	6	72	216	9.5256	.1323	25.872	.35933	28.028	.3893	.49163
22	26.4	6	72	216	10.4544	.1452	27.104	.37644	29.363	.4079	.52164
23	27.6	6	72	216	11.4264	.1587	28.336	.39355	30.697	.4263	.55225
24	28.8	6	72	216	12.4416	.1728	29.568	.41067	32.932	.4449	.58347

To obtain bending-moments, stresses, and thrusts in the last seven columns, multiply the figures in column by load per square foot, including the weight of material.

The preceding table of stresses is calculated by Gaetano Lanza, Ph. D., Professor of Applied Mechanics at the Massachusetts Institute of Technology. It gives the stresses or strains per square inch of the Timbrel Arches having a rise of ten per cent. of the span and supporting a distributed load of one pound to the square foot. The coefficient was taken from the tests already mentioned (pages 58 and 59) as its ultimate resistance.

In calculating the safe load which might be put on the arches, we use ten per cent. of these ultimate resistances, thus introducing a much larger factor of safety than is usually employed in such calculations. As a matter of fact the arches may be strained to within one-fifth or one-fourth of the ultimate resistance of the material with perfect safety.

To determine the safe distributed load per square foot in the table of stresses, it is only necessary to divide the coefficient 206 by the maximum stress at the crown, taken in the line of figures at the end of the table; thus, for a 10′ span 3″ thick, we have $\frac{206}{0.46222} = 4{,}457$ lbs. per square foot safe load.

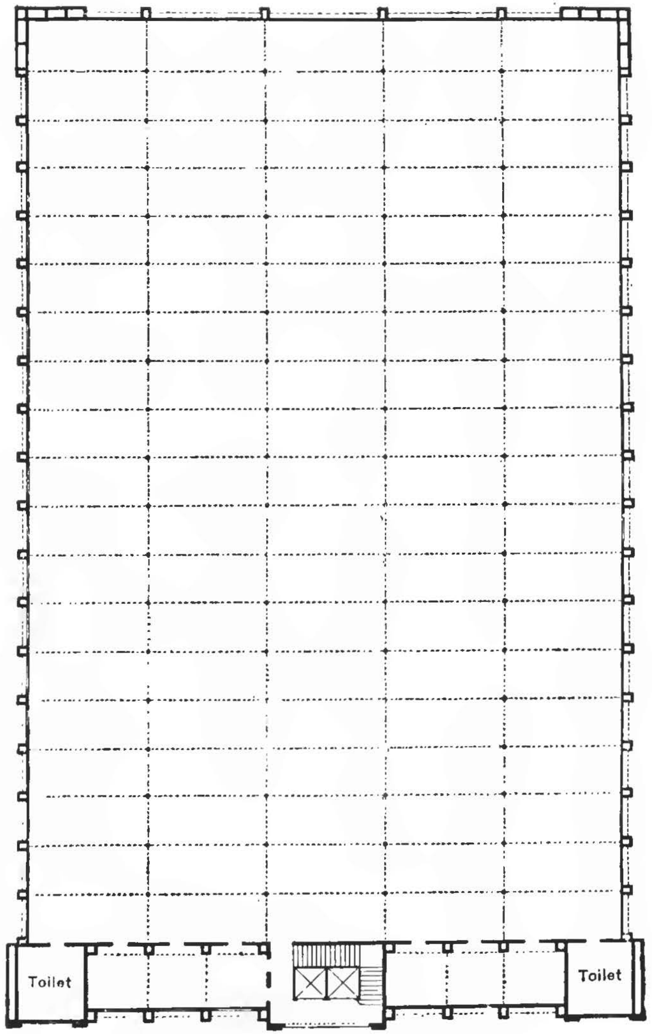


Fig. 49. Plan. Scale 1-16 in. to 1 foot.

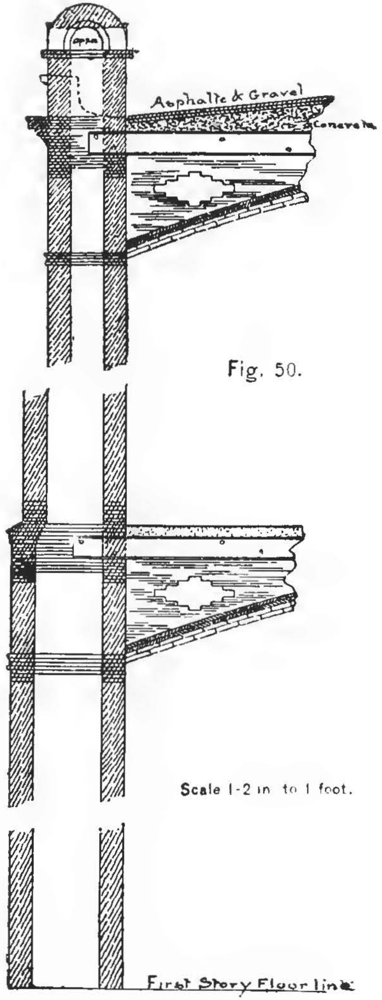


Fig. 50.

Scale 1-2 in to 1 foot.

Section through Piers.

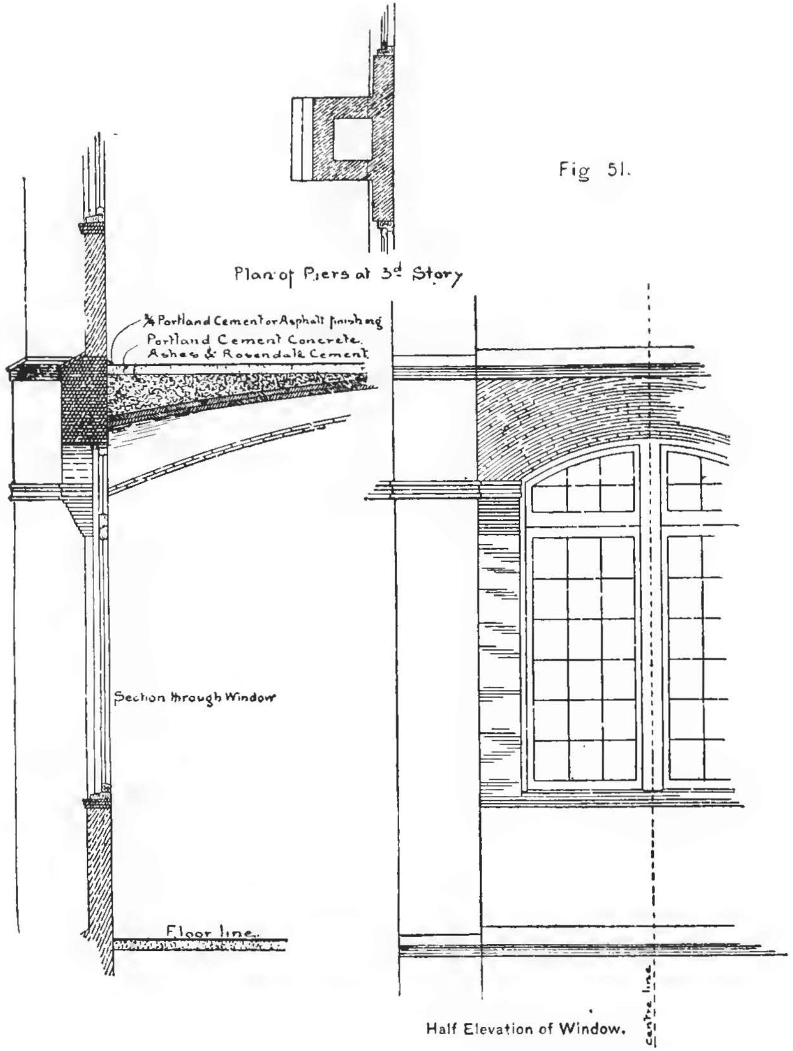
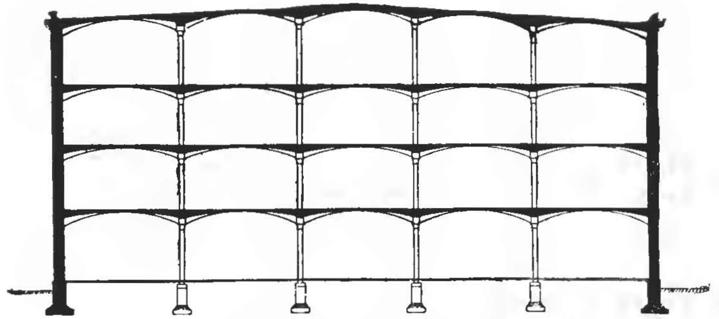


Fig 51.

Half Elevation of Window.

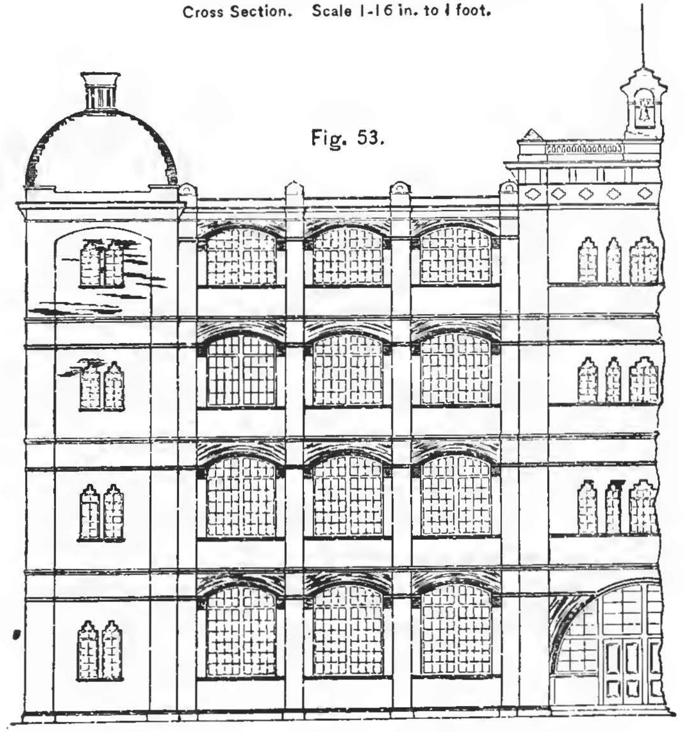
PLATE I.

Fig. 52.



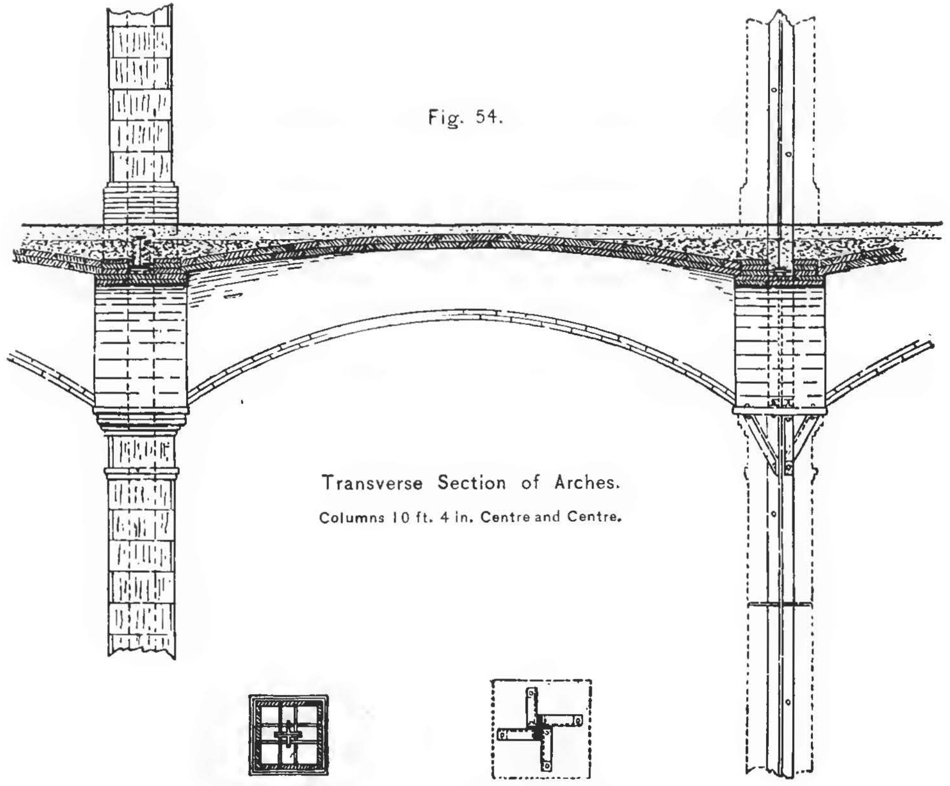
Cross Section. Scale 1-16 in. to 1 foot.

Fig. 53.



Fire-proof Factory. Part Front Elevation. Scale 1-8 in. to 1 foot.

Fig. 54.



Transverse Section of Arches.

Columns 10 ft. 4 in. Centre and Centre.

Plan of Columns.

Plan of Struts in Caps of Columns.

Fig. 55

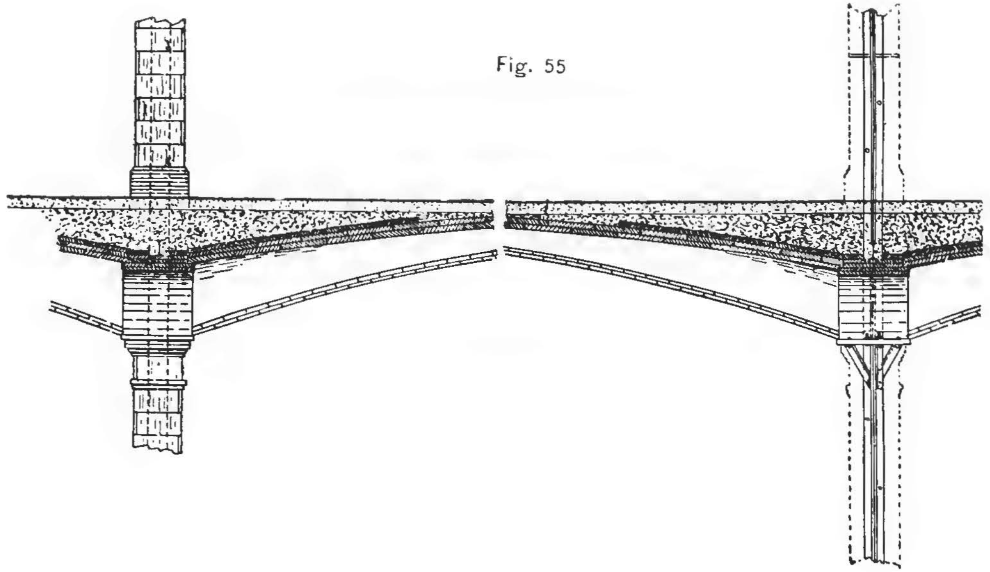
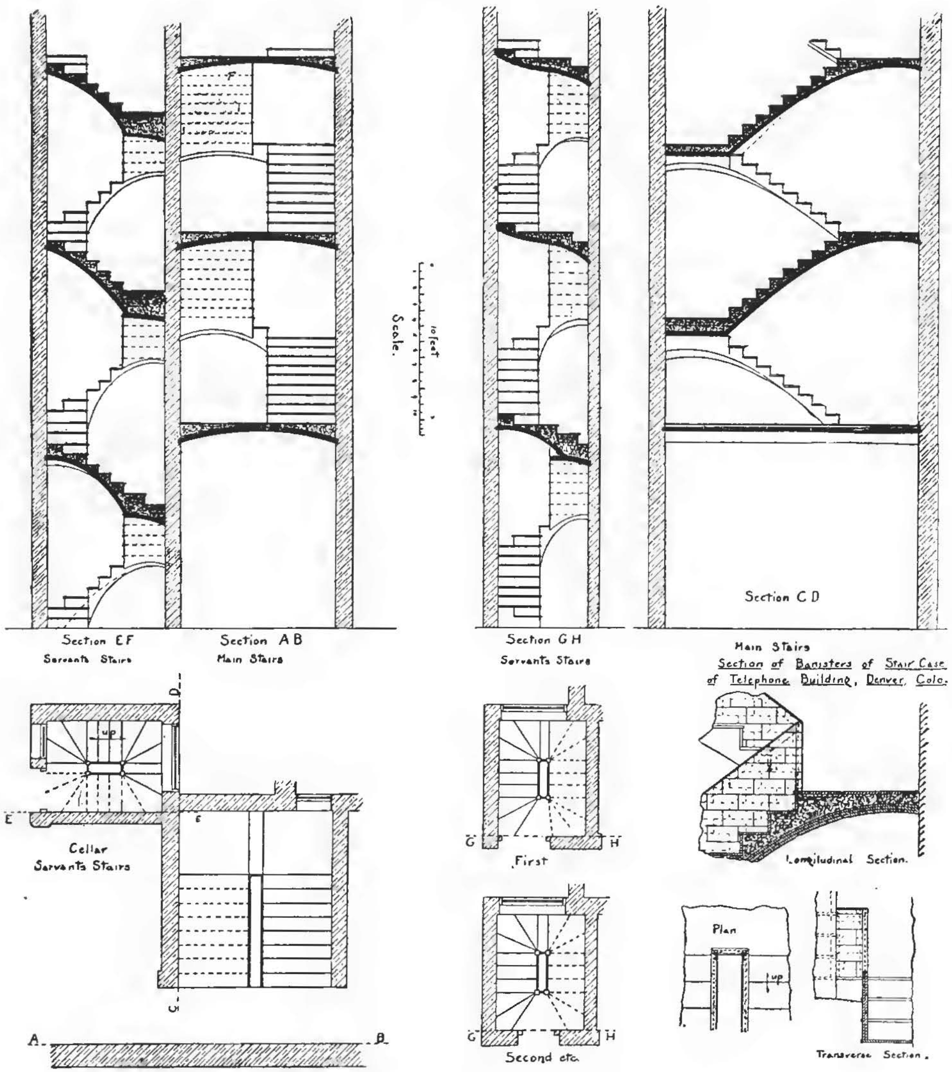


PLATE 11.

Stairs in Exeter Chambers, Exeter St. Boston, Mass



Guastavino Fire-Proof Construction Co

Stairs in 100th St. and Columbus Ave., New York.

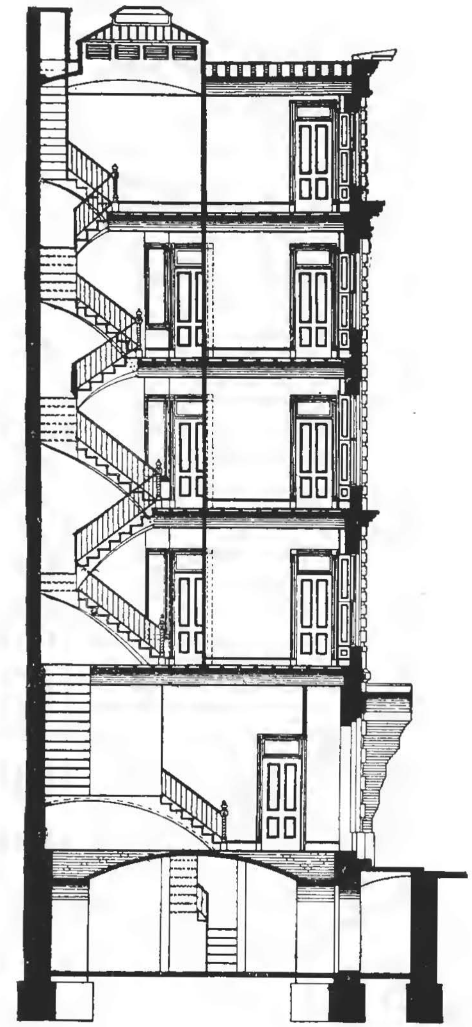
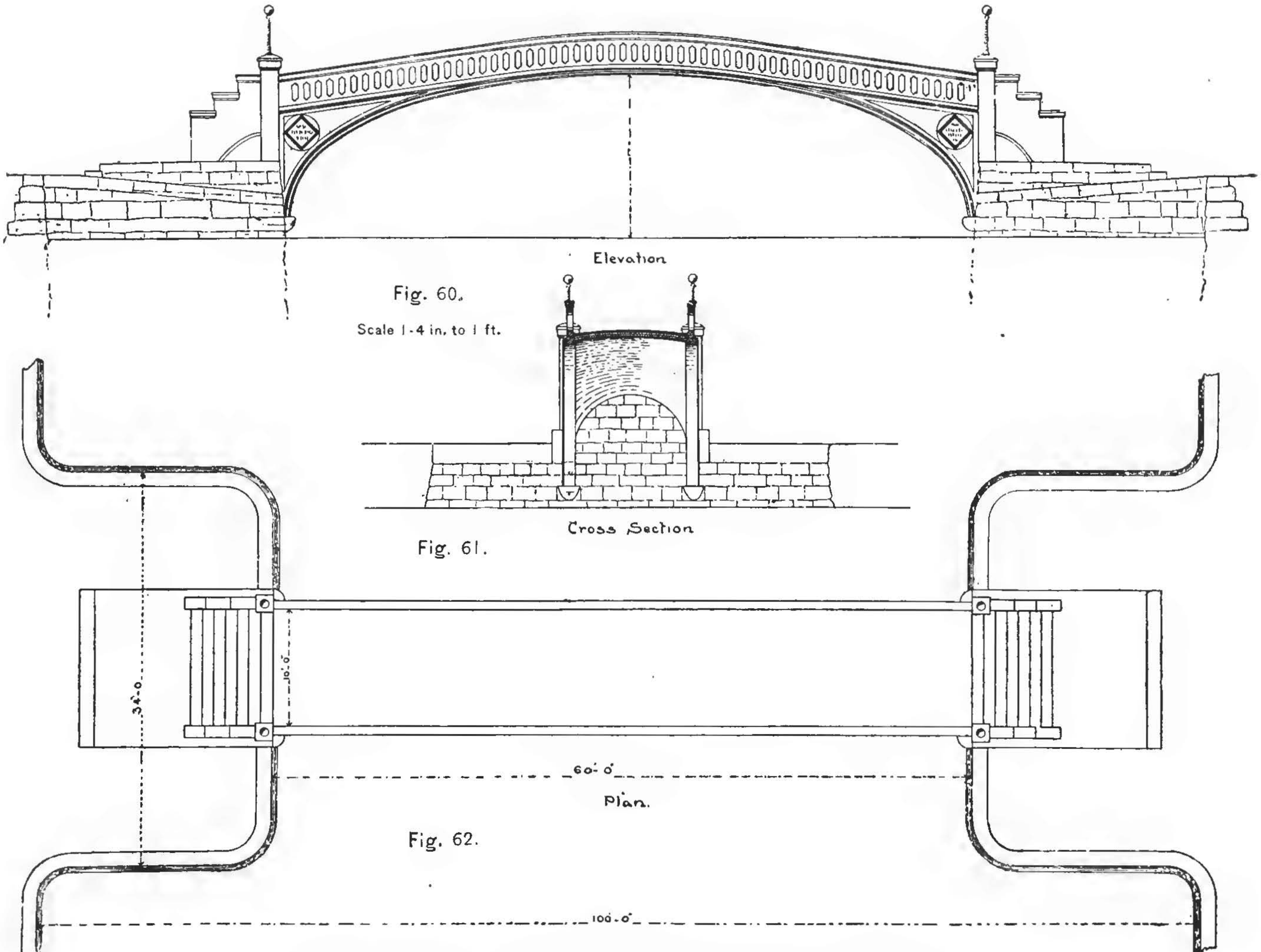


PLATE III.



Design for Bridge at Lincoln Park, Lake Quinsigamond, Worcester, Mass.

PLATE IV.