A Consideration of the Principles of Mechanical Arches as Applied to the Dental Arch*

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Did you ever stop to think why a barrel is stronger than a box; why the shell of an egg is so infinitely delicate and yet requires such force to crush; or, why the hull of the boat that rides the sea is built on a curve, instead of constructed in a flat form?

This almost sounds like the first chapter in one of your son's text books, and yet these are questions that should be of vital interest to us as Orthodontists. The answer to each can be made briefly and yet, what a tremendous amount of strength is expressed in the simple phrase, "The Principle of the Arch!"

Before delving into our own field of endeavor, I believe that a short resumé of the History of Architecture, with special reference to the use of the arch, will be of interest, in as much as the growth and progress of architecture and the application of the principle of the arch have been hand in hand.

It has been said that pre-historic architecture began when ancient man was forced to seek shelter from the inclemency of the weather or devise protection from his enemies. His first abode was a cave which, incidentally, we may note to be one of Nature's crudest forms of arches. As he progressed, his home also underwent development, and we find this primitive vault becoming a glorified edition, taking the form of igloos in the far North and sod huts among those who dwelt on the plains. Advancing beyond this point it is of decided interest to perceive that the first builder employed the canny methods used by birds and beasts around him and chose sticks and reeds for the framework of his home. The covering of this framework varied from hides and skins, utilized by the Red Man, to palm-covered dwellings of the Hotentot of the South Seas. In all of these structures some form of the arch appeared. It may have evolved by accident, invention, or was merely an inherited instinct carried over from the original cave of his ancestors. At first each individual was his own architect. The profession of Architecture began when man, desirous of building, employed a fellowman, specially trained in this field, to draw a set of building plans.

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Let us now briefly review the various types of architecture in the different countries and take cognizance as to what extent they utilized the principle of the arch.

The Egyptians, notwithstanding their tremendous advancement in other lines, as well as their colossal structural undertakings, did not employ the use of this important law to any great degree. Occasionally exception is found in an inverted canal or aqueduct. The majority of their edifices were built on the pyramidal principle—wide at the base and tapering towards the top.

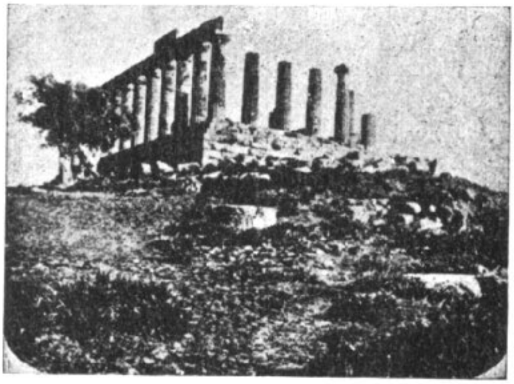

Figure 1

Example of Greek Columns, Showing Lack of Arch Support.

As we approach the subject of Grecian architecture, we find here, too, a highly developed race—one in fact without a rival in the art of building—yet endeavoring to achieve lasting beauty in their structures without the use of the arch principle. It is true that the Greeks did reach an unsurpassed pinnacle of architectural splendor, but their dreams of eternal endurance have crumbled with the centuries. It is the lament of all lovers of true art that not a single Grecian temple remains intact. With their knowledge of refinement, simplicity, and harmony of line, one cannot refrain from conjecturing as to whether some monument of that wonderful race of people might still stand today had they but incorporated into their plans the law of the arch in place of columns and lentils. Fig. 1.

Where the Romans gained their knowledge of arches and domes is still unknown, although it is generally believed to have been handed down by the Etruscans who were early settlers of Italy. The fact does remain, however, that they were the first to use arches extensively, and gave to the world the practical application of a principle treasured by builders throughout the Ages. Thus amply equipped, the Romans were able to build gigantic structures. The old flat-topped roofs of the Greeks and Egyptians were supplanted by vaulted ceilings; buildings of many stories arose; huge bridges spanned the rivers; aqueducts carried water to their cities; and roads led to homes where efficiency had developed to its highest degree. Fig. 2.

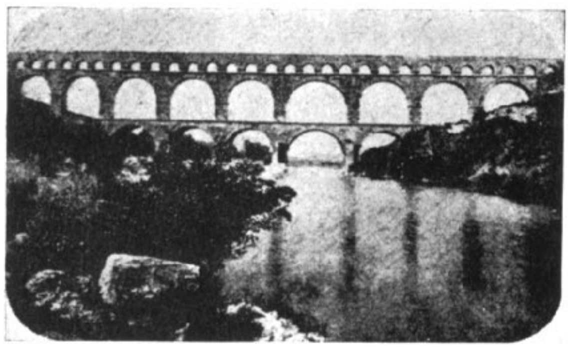

Figure 2

Ancient Roman Aqueduct, Showing Use of Arch Support.

Though connoisseurs of beauty are aware of the fact that the Roman did not surpass the Greek from an artistic standpoint, yet it is admirable to note his manner of borrowing that which was decorative from his neighbor, such as the beautiful gold-leaf interiors. However, he rejected the use of the column when it became apparent that arches could be built into the structures themselves. The latter procedure achieved a permanent result that is still a marvel to all mankind and permitted us to enjoy such gorgeous spectacles as the Colosseum, the Pantheon, the Forum, and the Arch of Hadrian in Rome. Fig. 3.

During the Middle Ages, the Roman Empire having divided, there came out of the East a form of architecture which was characterized by a horse-shoe arch—thereafter known as the Byzantine Arch. This, combined with the circular dome of the Romans, gave birth to many beautiful palaces and cathedrals—St. Mark's Cathedral in Venice and Santa Sophia in Constantinople being notable examples displaying this Moorish influence. Fig. 4.

Beginning with the Eleventh Century, we find the circular arch of the Romans replaced by the Gothic arch, a form which was used extensively

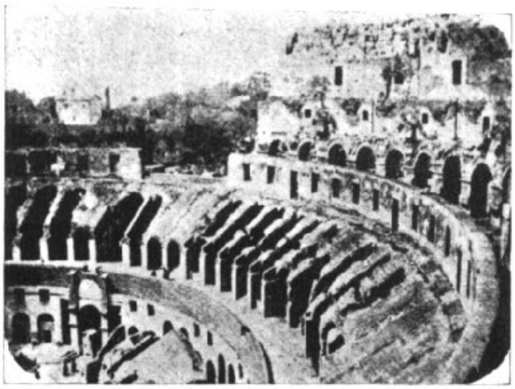

Figure 3

Arches employed in Roman Coliseum.

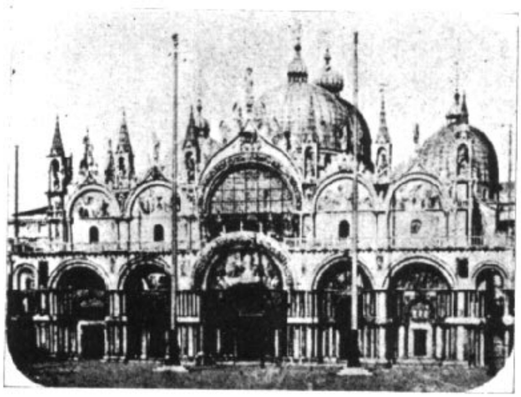

Figure 4

St. Mark's Cathedral—Example of Byzantine Arch.

throughout Europe. This type gave a feeling of height and made one look heavenward. Most appropriately do we observe its use in such outstanding cathedrals as Notre Dame, Rheims, Munich, and Westminster Abbey. Fig. 5.

Within this same span of years the leading architects of the day, most notably Michael Angelo, became aware of a decadence in their field, and, through earnest endeavor and research, brought forth a period known as the Renaissance. Recognition of the many beautiful qualities of the old Greek and Roman structures, combined with their advanced knowledge of the arch, brought forth a new beauty and strength in building such as the world had never known.

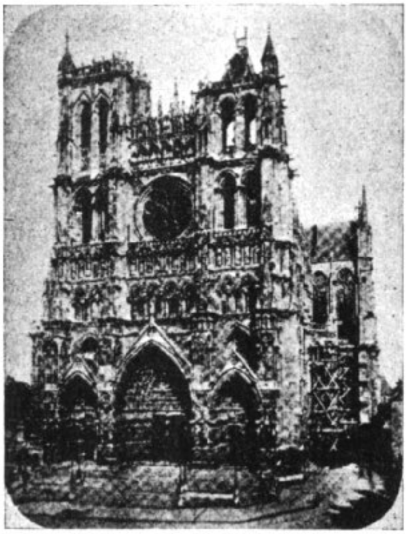

Figure 5

Notre Dame Cathedral—Example of Gothic Arch.

Veering to the East, it is interesting to observe that the Architecture of the various countries was governed by the knowledge they possessed, together with the material they had at hand, and also greatly influenced by climatical conditions.

The Japanese used the arch very little, as permanence was not the foremost thought in the construction of their homes. These had to be built of light wood or bamboo, because of the danger from earthquakes or an infestation of vermin which might sweep through an entire village necessitating destruction by fire.

In China we find the low, squatty-type home, with its peculiar sway-backed roof and curved eaves, allowing the sun entrance, yet protecting from the rain. Although one might term this roof an inverted arch, yet here, as in Japan, we find its presence generally lacking, as the elements are far too cruel to allow the natives a great deal of thought concerning construction beyond immediate protection. The exception is found in the Nipponese State, however, in the arches used in their small, wooden bridges, while an outstanding arch, used throughout China, is found in the form of a circular

Figure 6

Chinese Moon Gate.

gate through the walls. This is known as a Moon Gate, and, as the Chinese are a very superstitious race, they look upon it with especial favor considering it a good luck omen. Fig. 6.

Before leaving the Orientals, I might add that their Sacred Pagodas, found so frequently, attain their height and stability from the fact that they are built on the pyramidal principle. Also, in recent years, modern steel and concrete earthquake-proof buildings, are rapidly replacing the older type of construction.

In India we find man utilizing the natural arch in the form of rock cut caves. Whole villages are sometimes quartered in these excavations, as they are known to extend back as far as three and four miles. Here and there, square openings are installed for ventilation and light while, at intervals, pillars of solid rock are allowed to remain to support the roof. Notable, too, are the Temples and Monastaries likewise enhoused, the largest being the Ellora Temple. This was hewn from solid rock, about 1000 A. D., and its entrance is guarded by elaborate pillars and figures which are cut on the face of the cliff. Fig. 7.

Many magnificant tombs were erected in India and of these we find the Taj Mahal occupying a position of unsurpassed beauty. Fig. 8. Its white marble structure is topped by a dome 190 feet above the ground, while its

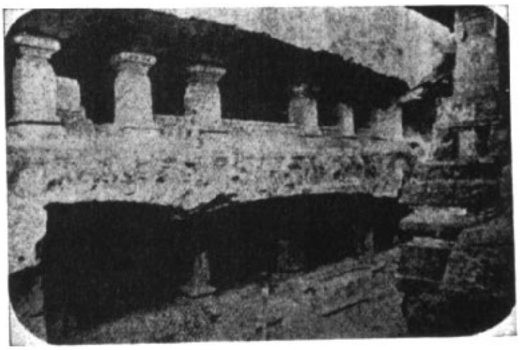

Figure 7

Rock Cut Caves—Ellora, India.

interior decoration is the marvel of all those who view its splendor. Aside from the structural qualities, it is unique in that it was erected in memory of a Princess, an almost unheard of custom in India. We also find ourselves fascinated by the tragic story of the French Architect, then a captive, who was blinded by the Maharaja when he saw the completion of this great masterpiece. The answer to this heinous deed was no doubt traced to the early Hindu belief, that the arch was an evil form, "in as much as its force was always working, and never allowed to sleep."

As to our own and other modern types of architecture, there is very little to be said at this time concerning its application of the arch. We know, only too well, the extensive use to which engineers have employed this principle. Fig. 9. One need but tour a great city, with its buildings, bridges, and aqueducts, to realize how man has nurtured and cared for that tiny thought-germ, implanted by Mother Nature when he was first given protection beneath the sheltering curve of a cave.

As an architect gazes in admiration, while standing before the Arc de Triumph, so do we, as Orthodontists, revere the Dental Arch, one of Nature's most beautiful creations. And yet, if we do not execute our problems, from a mechanical standpoint, in the same manner that Nature employes, or a builder uses, we are following a hit-or-miss procedure and are very likely to invite failure. We *must* have a balance of forces around the denture, and one of the surest and truest means of achieving this ideal is by molding our treated dental arches into harmony with a geometric design.

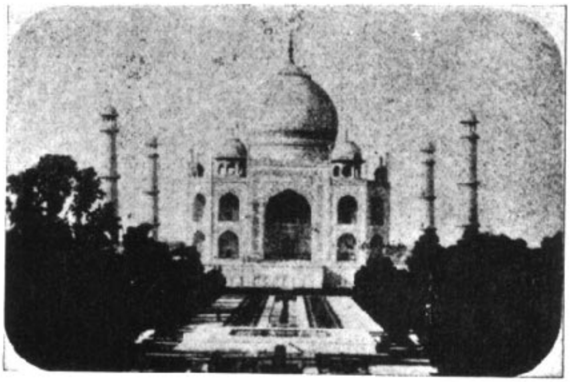

Figure 8
Taj Mahal, India.

The standard definition of an arch may be stated in the following terms: "An arch, in the art of building, is a series of stones or blocks arranged side by side in a curve in such a way that if the two ends of the arc or bow be kept in place, the portions of the entire arch support each other." The blocks or stones, are technically known as voussoirs, hence the term—voussoir arch. Though there are other types of arches used by builders, we will consider only this one, as it pertains more closely to our work.

A vault, for which we must have some consideration, is a continuous arch, and is known, in building, as a barrel or wagon arch. There is a slight difference between the principle of the arch and that of a dome. In the former, the line of action is in one direction only, and each block, or voussoir, supports each other in such a single line of action, while in a dome, the line of action is in every direction, and every block supports every other block in a universal manner.

In the structure of an arch we find it to be made up as follows: Fig. 10. The top stone, A, is known as the key-stone, and the lower blocks, B.B., which rest on the abutments, or supporting piers, are the springers. The side blocks, D, are called the haunches, and the lower surface or soffit, E, is called the intrados, while that of the outer surface, F, is termed the extrados. The rise of the arch, G, is the distance from the springers to the soffit, while the width of the arch is called the span, H.

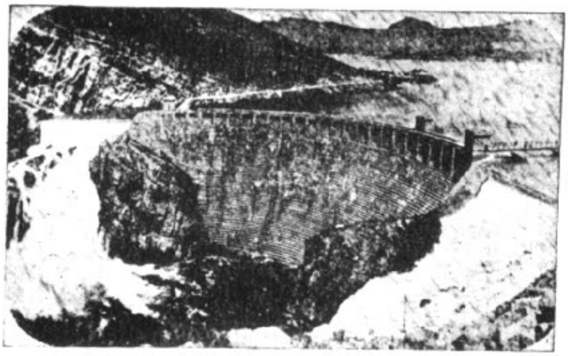

Figure 9
Roosevelt Dam—Example of Modern Use of Arch.

In constructing an architectural arch, the voussoirs must be supported until the keystone is inserted. This is done, today, by a central assemblage of timbers, bound together, with its upper surface of the same shape as the arch under construction.

There are various forms of arches, ranging from the circular to the flat. However, the only form which is of importance to us and with which we are concerned, is the circular—not only because its action is the simplest and easiest to understand, but also because it is the one most frequently used by Nature.

In the building of a voussoir arch, the architect has what he terms, a Theory of Stability. In order to conform to this he must determine, geometrically, the curvature of the arch, the weight it is to sustain, and, because every unit of the arch is active and working against its adjacent blocks, he must ascertain the line of force between the various blocks and just where this force will be distributed. The architect has named this the Line of Resistance but let us call it the Line of Force or Action.

A voussoir, or block, is divided into three parts—the outer third, the middle, and the inner third—and it is an established fact that the line of action must pass through the middle section of the block if the arch is to be mechanically stable. Fig. 11. It is also well for us to remember that when an arch is thus correctly calculated, it will balance and maintain itself, even though no mortar or cement is used in its construction.

Just as important as the arch itself are the buttresses which sustain it. The line of action passes down through their mass and, as in the arch, this line much be maintained within their middle third in order to effect a suc-

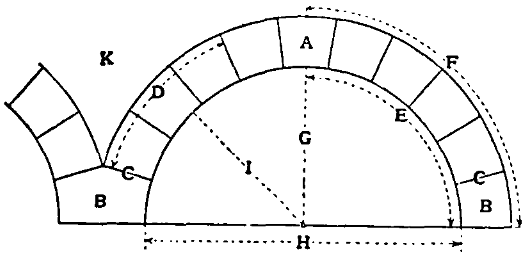

Figure 10

Construction of the Arch.

cessfully balanced result. Fig. 12. Usually these buttresses are made bulky and much larger than necessary, to assure safety. In some instances a buttress will be placed against the sides of the arch, that ample stability may be secured. Such supports are called "Flying Buttresses." Fig. 13.

As one continues to read through the volumes on arch construction technique, it is amazing to note the causes of failure in the mechanical arch and to find that the architect's problems are very closely allied to ours. I will herein note a few of the outstanding reasons for the downfall of arches: 1, Slipping of the voussoirs; 2, rotation of the blocks; 3, crushing of the arch; 4, failure of the buttresses. Do these sound vaguely familiar to you? They are actually taken from "A Treatise on Masonry Construction," by Baker.

By "slipping of the voussoirs" is meant that the haunches move in or out, according to whether the arch is constructed too flat or too pointed to stand the strain. In other words, faulty arch design. Fig. 14. "Rotation of the blocks" takes place when the line of action passes to the outer or the inner third of the blocks instead of through their middle third. The force actually has a tendency to rotate the blocks in the arch and thus cause the failure. Fig. 15. An arch will be crushed if the weight imposed upon it is greater than the strength of the material used. There can be but one result from such a force. An arch will also fall if the line of force does not pass through the middle third of the buttress. Fig. 16.

An arch may stand for some time, with the above faults incorporated within its structure, but let some unusual strain be placed upon it and it will soon demonstrate its weakness. This fact was clearly exemplified in our

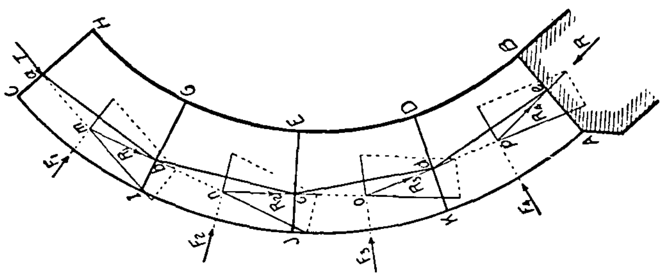

Figure 11

Line of Force Through Middle Third.

recent Southern California earthquake in which so many of us were vitally interested. Many of the buildings affected were constructed of brick, with perhaps a series of arches over a row of windows. The end abutment, or corner-piece, was apparently made too narrow—the line of force from the arches did not pass through its middle third but was flaunted into space. Consequently, as soon as the buttress collapsed, it allowed all of the dependent arches to likewise give way. When you hear undue criticism pertaining to construction, after such an upheaval, you may note, mentally, that probably all the blame should not be placed upon the material used, but some also upon the manner in which this material was employed. Fig. 17.

Having dwelt upon the history and structure of the mechanical, or man-made arch, let us briefly consider Nature's use of the arch principle. When we trace back the derivation of the word, arch, we find that it originated from the Latin, ARCUS, which means anything in a circle or arc. When once we become conscious of a subject—observe and meditate upon its origin—it is surprising how many examples we find, in all walks of life. So it is with the subject we have chosen to discuss here.

Consider the earth and the planets—they are spherical in form, and a sphere or ball has a perfect arch or dome principle. Let us look at Nature's

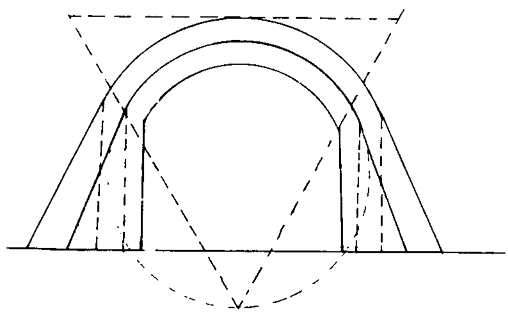

Figure 12

Line of Force in the Buttress.

caves, such as the Carlsbad Caverns and likewise the Mammoth Caves in Kentucky. Gaze upon some of Nature's natural bridges, such as the Rainbow Bridge in Utah, Fig. 18, and the Natural Bridge of Virginia up which George Washington climbed and carved his name. Even a tree, a flower, or a mountain, in fact, anything that Nature produces—study them for a time and you will perceive that the principle of the arch will manifest itself. It appears that she endeavors to combine beauty, strength, harmony, and, may I also add the word balance, in all of her undertakings. When this is achieved, I have yet to find one single instance where the principle of the arch is not introduced in some form.

It is singular, with Nature flaunting this principle to man so universally, that he was so slow in grasping its truth. Perhaps it was because the example was too close for him to appreciate, or he did not apply his intelligence to that extent. At any rate we do know, after a perusal of the history of the arch, that man has employed the arch principle but for a comparatively short time, in contrast to Nature, for it seems to have been one of her basic laws, since the beginning of Time.

Let us now observe its use in the human body. I will enumerate some of the outstanding arches found therein. There are the arches in the foot, in the head of the femur, the pubic arch, the thorax, the zygomatic arch and, lastly, the dental arch, which we will now consider in detail.

In this dental field we find there are many arches, and, of course, we all know that when they are normal, they function harmoniously and work

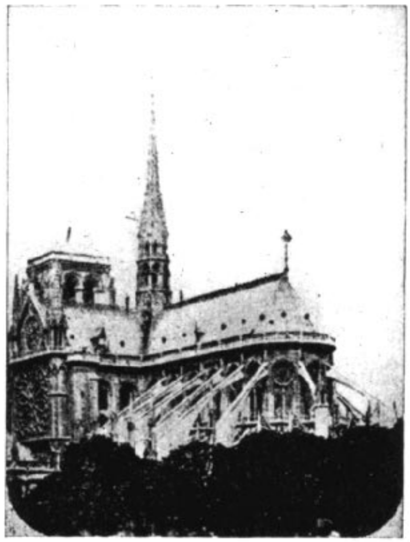

Figure 13
Example of Flying Buttress.

in conjunction with each other. I will, however, only discuss the three outstanding arches in the organ of mastication and we will examine them from a purely mechanical standpoint.

First, we have the so-called lower dental arch; second, the upper dental arch; and third, the arch, or vault, which originates at the base of the mandible, on one side, passes up through the lower teeth to the upper teeth and over the roof of the mouth, then down on the opposite side.

We have always considered all the teeth in the mandible as being part of the arc, but, after studying the mechanical arch and its principles, it seems that the only teeth that are in the true curve itself, are the six anterior units. The buttresses for this bow, are the bicuspids and the molars. The cuspid can be compared to the springers and the remaining teeth, to the haunches.

If you will take a normal denture, one that has stood the test of time, and describe an arc which passes through the contact points of the lower six anterior teeth, you will find that you have a perfect semi-circle. If that line is then allowed to pass back through the bicuspids and molars, it will

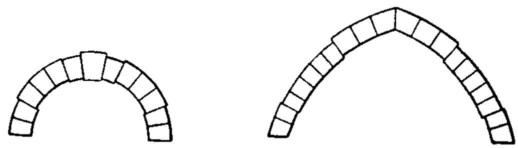

Figure 14

Slipping of Haunches due to Faulty Arch Form.

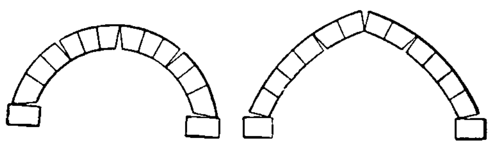

Figure 15

Rotation of Blocks Due to Line of Force Not Passing Through Middle Third.

be on a straight line, and pass through the middle third of the teeth—that is, through the contact points. Fig. 19.

To prove this, for our satisfaction, we have constructed geometric charts for all shapes and sizes of arches. We have made them for as great a variance of types as possible and have applied them to normal mouths—that is, as nearly normal as it is possible to find—and, without one exception, when this graph was applied, the line ran as follows: The anterior arc, running from cuspid to cuspid, was in a circle, and then the lines passed divergingly backward from the cuspids through the bicuspids and molars. Fig. 20. Of course this arc and the divergence of the lines, varied according to the type, size, and shape of the individual teeth in the anterior segment.

After considerable observation and study of a great many cases, it is my personal opinion that the bicuspids and molars are acting buttresses to support the anterior arc. Taking into consideration the fact that the molars turn lingually from the bicuspids, we find, nevertheless, that the line passes straight back regardless of this deviation and, in order to support this line of force, we have, in the lower jaw, the heavy flanges of the rami and the body of the mandible itself. These are bony buttresses acting to support the tooth buttresses. Fig. 21.

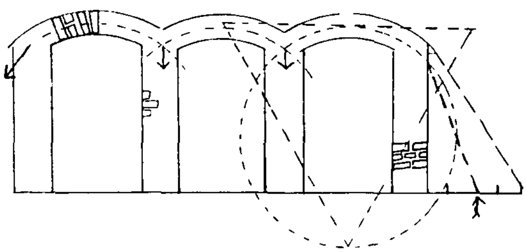

Figure 16

Example of Inadequate Buttress.

What has been said regarding the mandibular teeth applies equally to the maxillary dental units. In the upper jaw, however, we find the heavy pterygoid processes of the sphenoid bone and the jugal ridge acting as flying buttresses to support the upper bicuspids and molars—the pterygoid processes acting posteriorly and the jugal processes laterally. Fig. 21.

The third important arch of the denture is that part which we are prone to call the roof of the mouth. This is really a vault and would be termed, mechanically, a wagon vault. When we examine a cross-section of a skull, or even a set of models, we can perceive that the arc of this vault is only in the roof of the mouth, and the support, or rather the buttress for this arc, is the teeth in the upper and lower jaws, when they are in apposition. Fig. 22.

If a theoretical arc is described through the middle third of the bony structure of the roof of the mouth, and if lines are passed downward, so as to geometrically and mechanically support this arc, it would be found that these lines passed, consecutively through the roots of the upper teeth, through their crowns, to the crowns of the lower teeth, through their roots and finally, were absorbed somewhere in the body of the mandible. Fig. 23.

It is almost needless to mention how important and necessary it is that the teeth in the upper and lower jaws be together and in normal occlusion in order to mutually support one another and sustain the vault of the roof of the mouth. We know that the teeth must be in their correct relation in order to maintain that very fine line of balance upon which these arches depend for their mutual stability.

If a geometric chart is prepared for an upper and lower dental arch that has proved itself stable and remained normal under the ordinary wear

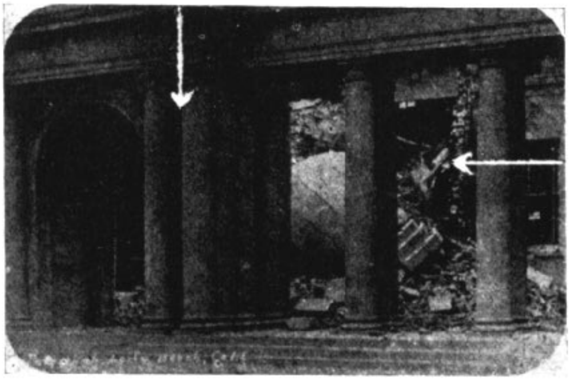

Figure 17

Earthquake Damage, Showing Result of Correct and Incorrect Buttress Support.

and tear to which a denture is subjected, it is uncanny to find the symmetry and harmony that exists between these two drawings. Fig. 24. Also, when these charts are applied to their respective arches, it is found that the line passes through or very close to all of the contact points between the teeth. Fig. 20.

As additional buttresses to the bony structures, which we have already mentioned, we have, on the inside of all these arches, the muscular support of the tongue, which exerts its force in an outward direction and aids in supporting the arc from the interior. On the outside are the extra-muscular buttresses of the lips and cheeks, acting with an inwardly directed force to help maintain the arches from displacement laterally.

There is sufficient evidence, when Nature creates an arch, that she follows definite, mechanical lines. Otherwise collapse of that structure would be inevitable. Dr. Angle, too, in his teachings, stressed the principle that when a dental arch was designed it was planned according to the type, size, and shape of the individual teeth. Hence it stands to reason, that if the Creator uses this plan, surely we, as humble Orthodontists, should have some mechanical information upon which to base our work. This draft can be varied according to our individual conception of the particular type of person upon which it is to be applied, but experience will disclose the fact that the diversity need be but slight.

Why do our treated dental arches fail and collapse? If we will turn back and briefly review the causes of why a mechanical arch is not success-

Figure 18

Rainbow Arch, Utah.

Also Chart Applied.

ful and substitute the word "tooth" for "voussoir," we will arrive at practically the same conclusion. Let us recall them and apply these reasons to our own problems.

First, slipping of the teeth, either bucally or lingually. In a mechanical arch this is due to faulty arch design—why could not this apply to our arches?

Second, rotation of the teeth. We are all aware of the influence this will have on an arch. A builder informs us that this is due to the fact that the line of action does not pass through the middle third of the voussoir. This is true in many cases, but usually our relapsed rotations can be laid either to inadequate retention or insufficient treatment.

Third, crushing of the arches from too much pressure. Of this we need no reminder. Whether its source be the lips, cheeks, tongue, sleeping habits, or what not, when an excessive or an unbalanced force arises, the downfall of the arch is inevitable.

Fourth, failure of the buttresses. In regard to this phase, we need no better example than that of a mouth-breather, for if the teeth, particularly

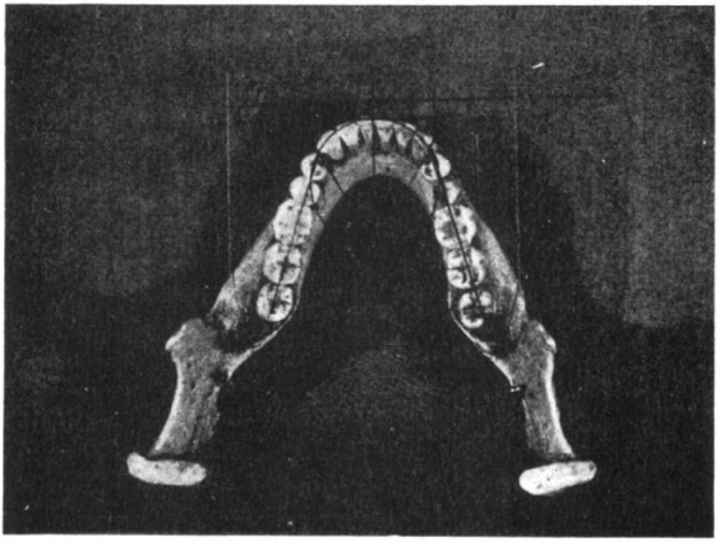

Figure 19

Lower Dental Arch, Showing Natural Buttress.

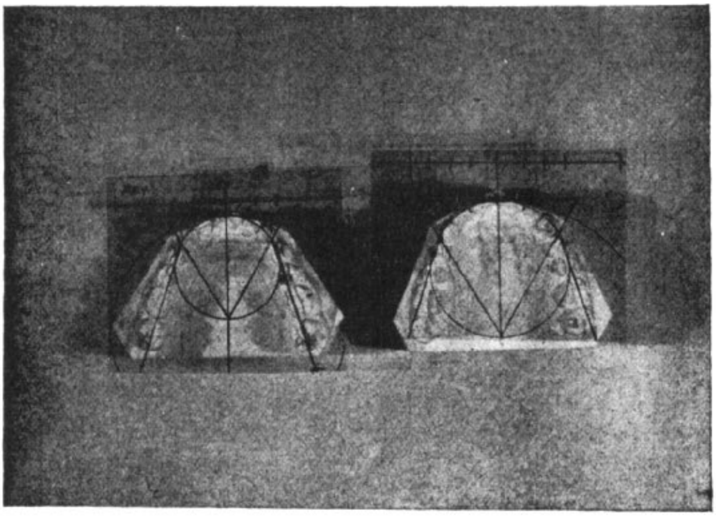

Figure 20

Chart Applied to Proven Case.

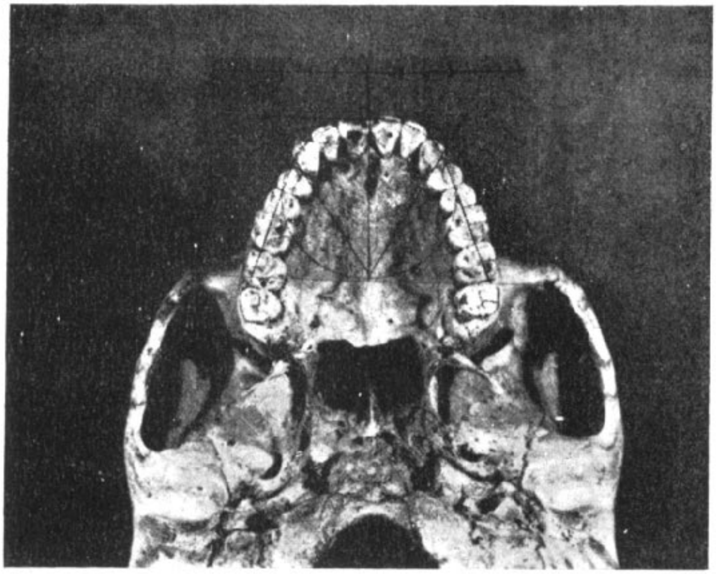

Figure 21
Upper Arch with Buttress for Support.

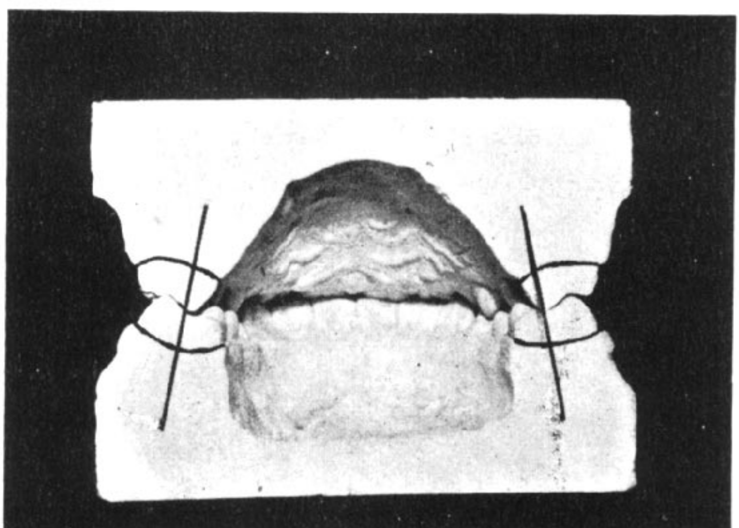

Figure 22
Cross-Section Through Model Showing Vault and Line of Force.
(Text Book of Orthodontia.)

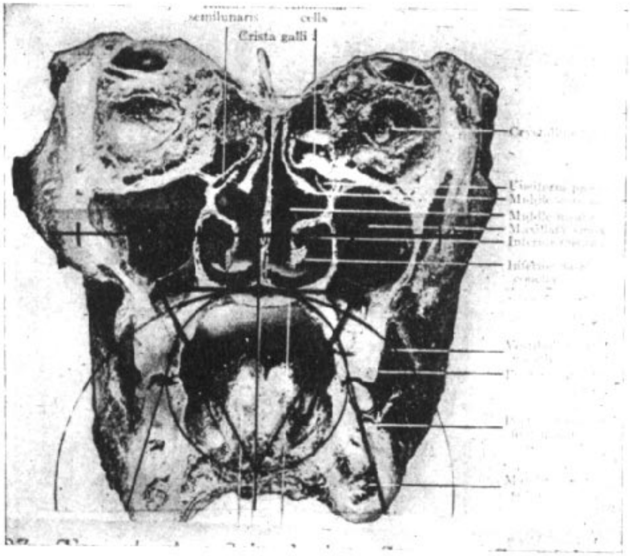

Figure 23

Chart Applied to Cross-Section of Skull.

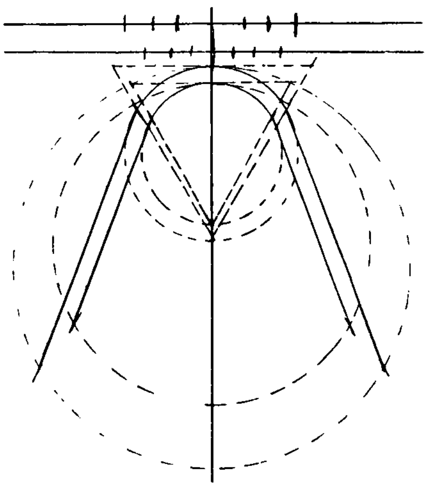

Figure 24

Comparison of Upper and Lower Chart.

the molars and bicuspids, of the upper and lower arches are not in apposition, the value of the buttresses is ruined and we have no bearing of one arch upon the other. Consequently there is no foundation for the vault of the mouth. This leads to but one conclusion—collapse of all arches.

Therefore, in converting an abnormal mouth into a normal, we must make use of correct arch design, avoid rotations, eliminate crushing forces and establish adequate buttresses.

In a final comparison of the dental arch to the mechanical, I will cite only a few variances, although, of course, there are many. A mechanical arch must be constructed to withstand a load from only one direction, usually a downward force, while an Orthodontist must form an arch that will sustain stress from many directions. Here, the engineer has the advantage. He also has the upper hand in working with inert, square blocks, with wide, flat surfaces, while we have rounded, building units which meet only at one small contact point. We have this supremacy, however, in that we are afforded buttresses and supports externally, internally, posteriorly and anteriorly, while the architect has abutments only at each end of the arch.

However, no matter what these variances in arch building may be, there is one common principle that must be observed, whether the arch is to be made by human hands or by the Master Builder of the universe. This law reads as follows: In order to maintain an arch of a prescribed curve in stable equilibrium, the buttresses must diverge in a certain definite direction. In conformation with this law, the design of the architectural arch and that of the dental arch must be harmonious. Therefore, why do we not, as skillful and sensible workmen, appropriate a few of the architect's fundamental concepts and thereby create dental arches of such lasting beauty and strength that they will rival even those similarly formed structures created by the great builders of ancient Rome!

Hollywood Security Building