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ARCHES
IN ARCHITECTURE

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by

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In memoriam

to my Father

JAN STARCZEWSKI

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INTRODUCTION.

Vitruvius in his Ten Books on Architecture [49] wrote:

"... the outermost piers must be made broader than the others, so that they may have the strength to resist when the wedges, under the pressure of the load of the wall, begin to press along their joints towards the centre, and thus to thrust out the abutments. Hence, if the piers at the ends are of large dimensions, they will hold the voussoirs together, and make such works durable."

The Romans knew and understood the structural value of the arch. They applied it consciensly getting, at the same time, interesting architectural solutions.

Indeed, the arch as no other element, blends into one issues of construction and architecture, strength and beauty.

The purpose of this thesis is to analyse the arch; its importance in the past and its potentials in contemporary architecture.

Part 1 of the study is devoted to an engineering analysis of the arch as a structural element.

In the second part, I have studied the arch throughout the centuries to discover a continuity of development due to continuous progress in technology, changing social demands and aestethical trends. I have included a considerable number of examples of buildings in Poland not known in this country in spite of a lot of information on English, French, Italian, German, Spanish or even Scandinavian architecture.

In the last part, I have presented a number of interesting examples of the XXc arches and I have attempted to answer the question as to what future arches may be.

1. ARCH AS A STRUCTURAL ELEMENT.

1.1. IDEA OF ARCH IN COMPRESSION STRUCTURES.

The building materials available in the early stage of human civilizations were of non-homogeneous type. Both stone and brick resist compression well while their tensile strength generally does not exceed 1/10 of the relevant compressive strength.

It may be assumed that in flat elements covering simple spans between vertical supports, bending may result in equal stresses, compressive at the top, and tensile at the bottom, both in the middle of the span.

The strength of the element is determined by a smaller value, i.e. the maximal allowable tension. This makes an uneconomical use of material and limits the span to be covered.

Of the traditional materials only wood works well both in compression and in tension. However, the early builders did not master the art of connecting wooden members so most of the advantages of this material had to be realized much later. The tendency of replacing wood with stone and brick in bigger and more important buildings and constructions is explained by their better resistance against atmospheric factors, against rot and insects, and the smaller risk of fire hazard.

In this situation only the arched constructions, in which tension is practically eliminated, could cover bigger spans.

1.2. PRINCIPAL STRESSES. JACK AND SHAM ARCHES.

The difference between an arch and a beam is reflected in visual notation, which is not necessarily in agreement with the laws of statics. If we analyse principal stresses, we will see that the difference in shape may not always mean difference in the statical work. From the point of theory, an arch may be subjected to bending, and thus considered as a curved beam. On the other hand, any beam in bending works as an arch and at the same time is a suspended system (Fig. 1-1).

In jack arches, lower bonds break open, so that the bottom part of the lintel simply does no work, and owing to the friction is hanging on to a hidden invisible arch structure (Fig. 1-2). We can imagine the jack arches as reinforced concrete beams with masonry instead of concrete and without any reinforcement.

An analysis of the statical work of an arch has been made possible on a presentation stand shown in Fig. 1-3. The stand has been designed for the technical lectures series at Virginia Tech.

The stand, made as a plastic frame, has a place for an arch and a beam. Both elements have the same cross section and the same span. Both are made of the identical photoelastic material. The load applied from both directions has the same value. A uniform distribution of the load has been secured by rigid brass elements shaped to fit the loaded elements. Between the brass rods and plastic models special gaskets, made of rubber tube, have been placed.

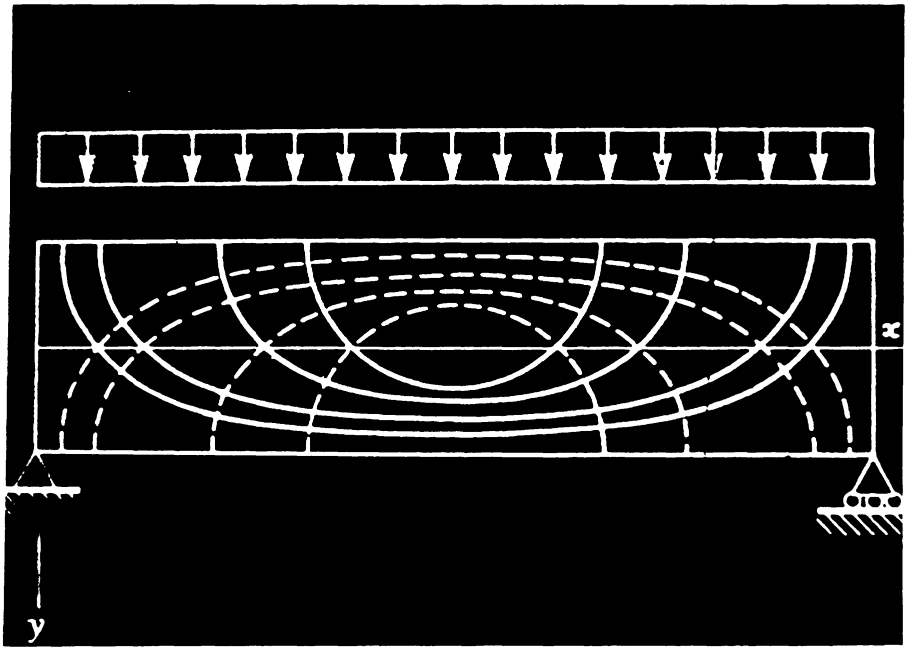


Fig.1-1. Principal stresses trajectories for simple beam under uniform load.

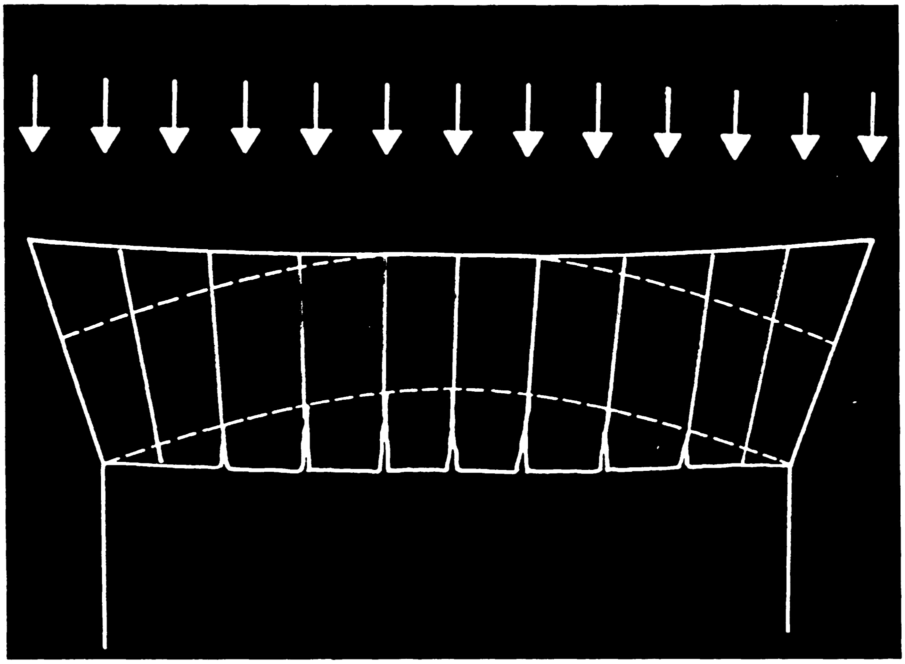


Fig.1-2. Idea of a jack arch. Small cracks, here enlarged.

The dotted lines indicate a hidden arch action.

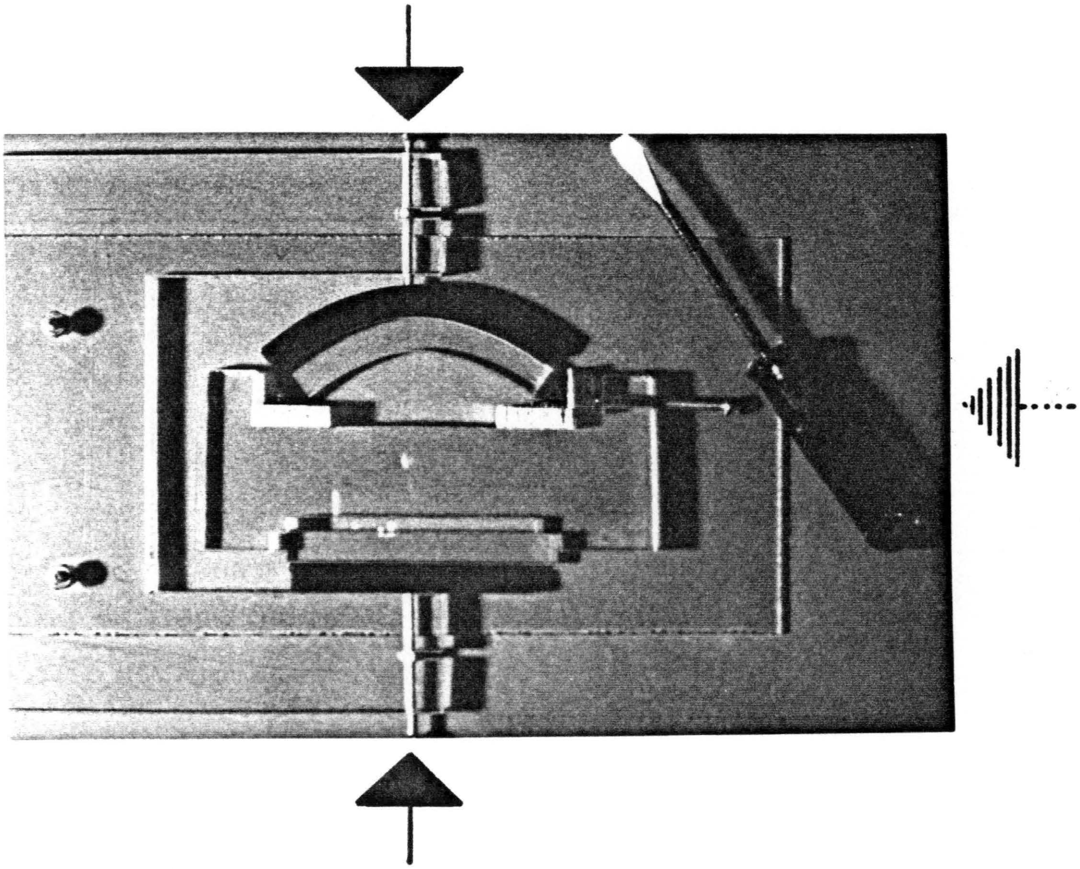


Fig.1-3. Presentation stand made at Virginia Tech.

The arrows mark direction of external forces.

The results of the experiment are shown in Fig. 1-4. The black fringes in the middle of the beam, as well as of the arch, represent the neutral axis. The number of fringes in the models indicates the the strains, which can be translated into the stresses.

The maximum bending moment in both elements is in the mid span. In this case the number of fringes in the beam has been doubled, when compared to the arch, even if it has been bent and is working as a curved bar.

Continuing the experiment and maintaining the same value for the vertical load, we apply a lateral force, imitating a tie, to the head of the arch. The value of the lateral force is increased continuously untill the moment, when the fringes have disappeared.

Elimination of all the fringes may mean the same strain throughout our arch. It may mean, also, no strain at all - but we know that this can not be the case, since fringes in the beam have not changed, proving that the values of the applied forces have not changed.

Our goal has been achieved. We have proved, what is known in engineering practice -- that a parabolic arch, with a tie, or two hinges on immovable supports, when the load is uniform and static, gives an optimal solution.

The enlarged photographs of the arch, with and without a tie, are shown in Fig. 1-6 and Fig. 1-7.

It is interesting to notice the distribution of stresses in mid-span cross-section of the beam, and at the crown of the arch.

Let us assume that stresses are subject to Hooke's law. The diagrams of stresses should look like those shown in Fig. 1-8.

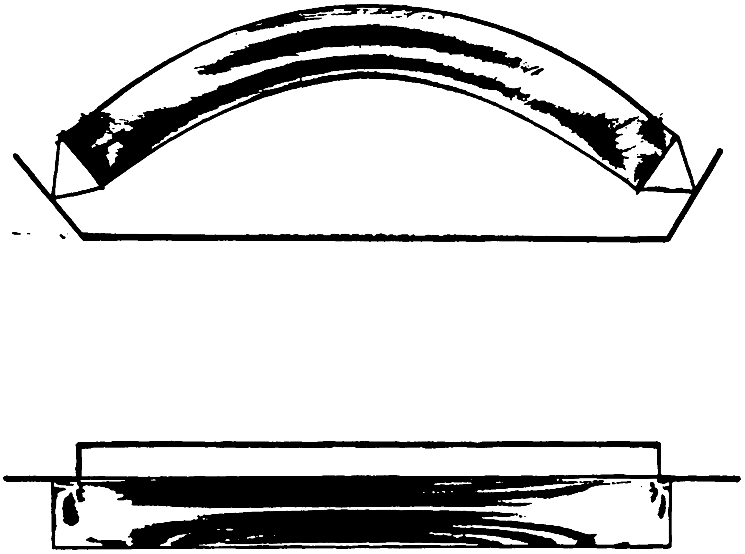


Fig.1-4. Photoelastic study.

Beam and arch exposed to the same vertical uniform load.

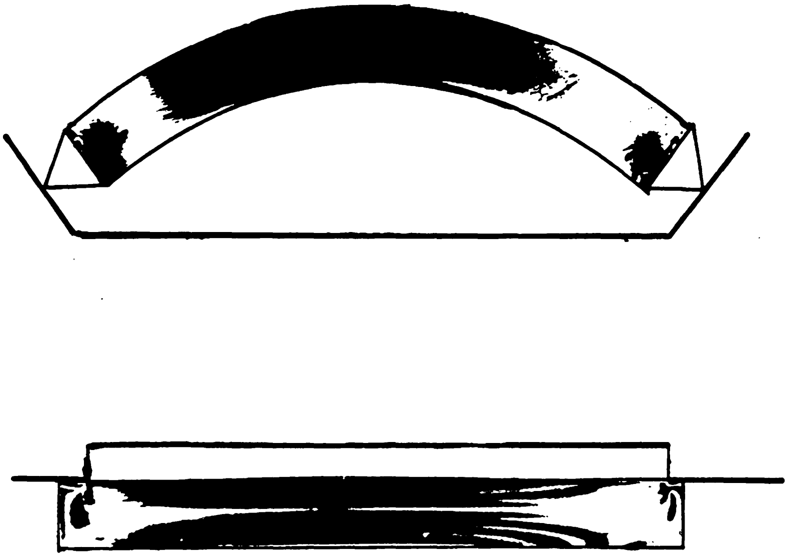
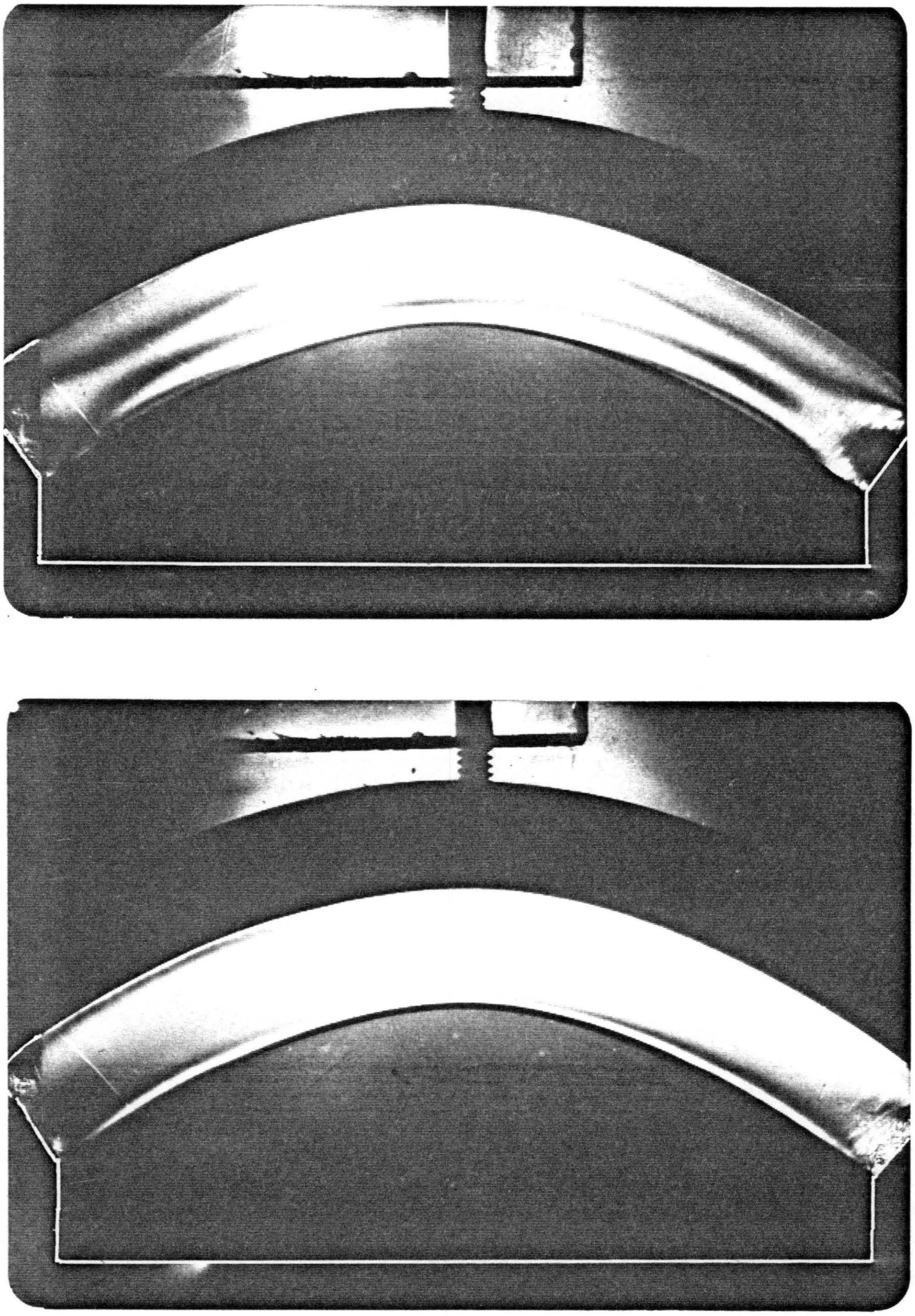


Fig.1-5. Photoelastic study.

Beam and arch exposed to the same vertical load as in Fig.1-4.

Horizontal force exerted on the arch to eliminate bending.



Figs. 1-6 & 1-7. Detailed image of fringes in the arch. Upper - in bending; lower - in compression, after a horizontal force has been applied, to counteract the thrust exerted at the supports.

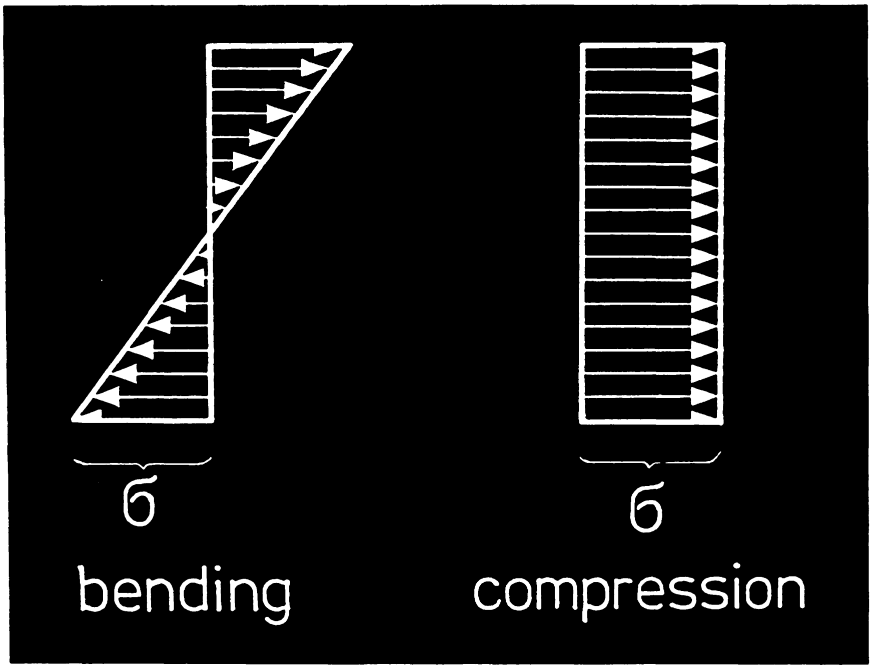


Fig.1-8. Diagrams of stresses, in bars exposed to pure bending and compression, according to elastic theory.

The theoretical area of the stress diagram in the arch is twice as large as in the beam. This could suggest that the bearing capacity of the arch of the same cross section as the relevant beam should be twice as big. However, in reality the relationship strain - stress is not linear, and in the arch, when under compression, buckling may occur. Still the bearing capacity of an arch, when compared to the bearing capacity of a beam of the same size, is greater.

A pure compression takes place only in the case of a resultant compressive force acting in the centroid of the given cross section. When the force is eccentric, it can be projected on the axis running through the centroid, and its non-axial performance may be expressed by the scalar value of the force multiplied by the eccentrity -- i.e. the distance between the applied force and the centroid. The latter is simply the bending moment of the said force about the centroid.

The effect of compression and bending in the rectangular cross section of an arch is shown in Fig. 1-9. When the resultant force is acting within the center one-third of the width of the cross section, there is compression in the cross section. When the force is exactly in the centroid - compression is uniform throughout the cross section. When the force is in one-third of the width of the cross section, the distribution of stresses is linear, and equals zero at the edge on the opposite side of the cross section.

The central one-third of the cross section is called "the core of the section". We see, that if the resultant force does not act outside the core of section, the bar is in compression. When the force acts outside the core of section, bending occurs, and on the side of the cross

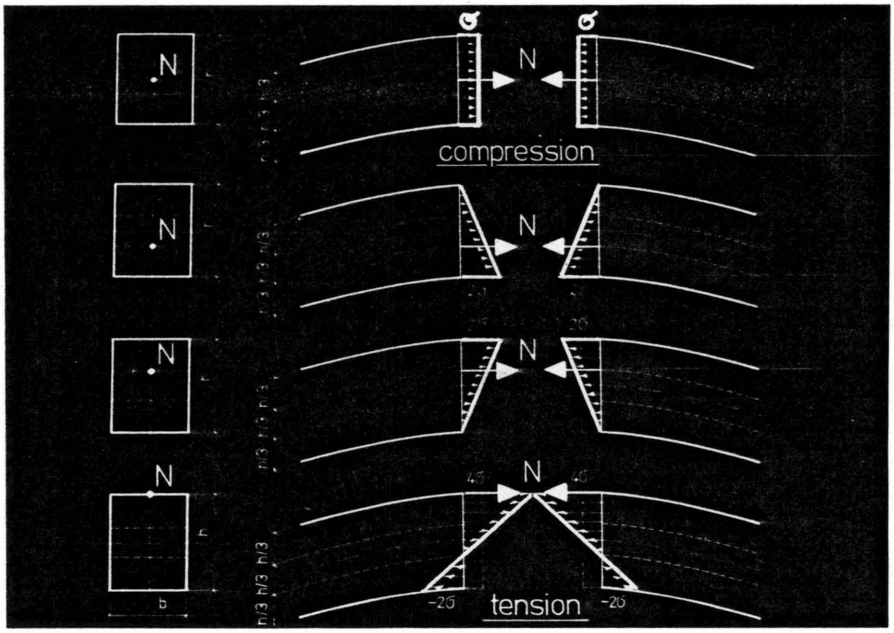


Fig.1-9. Diagrams of stresses in the cross section of the arch for different location of resultant force N.

section, opposite to the side on which the force is acting, tensile stresses occur.

Thus, the basic principle in arch design is to keep the resultant force within the core of section.

Different arches have been tested for statical schemes, curvatures, and cross sections. Various load patterns have been applied. The two equal concentrated loads placed at the 1/3 and 2/3 points of the beam provided interesting analyses of the pure bending in the middle of the span. The typical "onion shaped" fringes represented concentration of stresses near the central hinge in three-hinged arch. The same phenomena can be seen under the points, where the external forces have been exerted. For the experiment, the same testing stand, as described above, has been used (Fig. 1-10).

In the figures 1-11 to 1-13, fringes are shown in the beam and the two kinds of arches under the symmetrical concentrated loading.

The experiments, quoted above, have dealt with symmetrical loading only. Practically, compression prevails only in massive symmetrical arches. The more slender an arch, the greater the probability of bending. Slender arches are especially sensitive to assymetric loads (compare figures 1-14 and 1-15).

The recent studies undertaken by R. Mark of Princeton, and W. Clark of Queens College [12] on the gothic cathedrals, have scientifically demonstrated the correctness of their construction. The arched constructions of the cathedrals of Bourges (Fig. 1-16), Notre-Dame de Paris (Fig. 1-17), and Amiens are not only transmitting the vertical loads to the foundations, they also resist lateral forces exerted

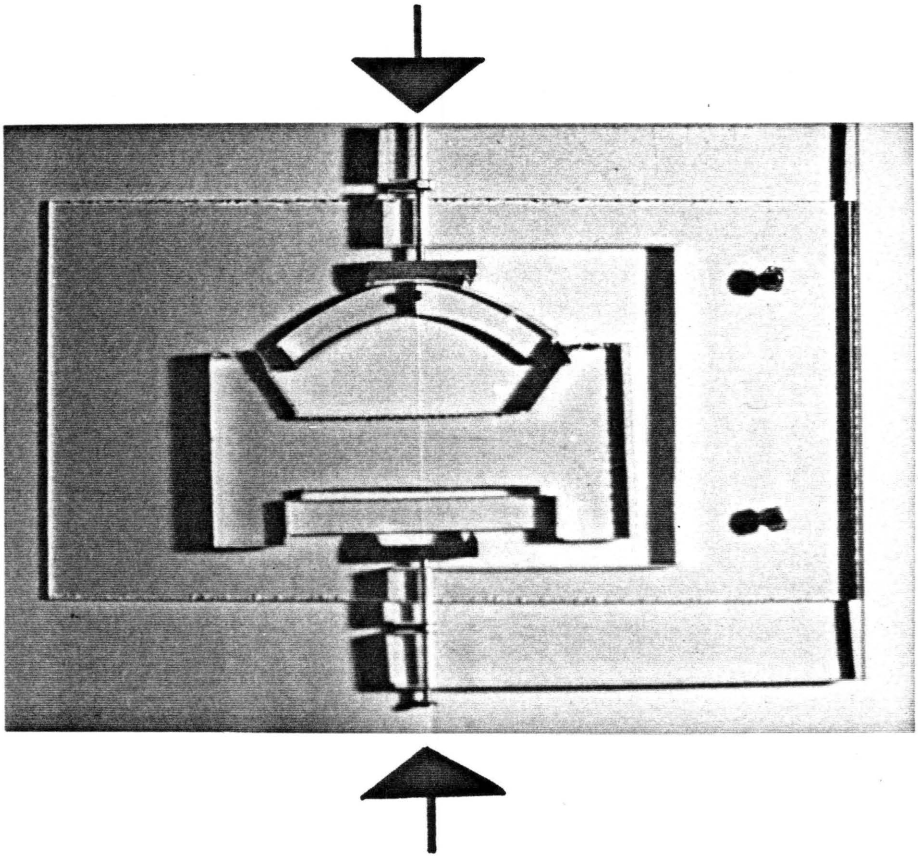


Fig.1-10. Three-hinged arch and a simple beam on the testing stand made at Virginia Tech. The arrows indicade direction of external forces.

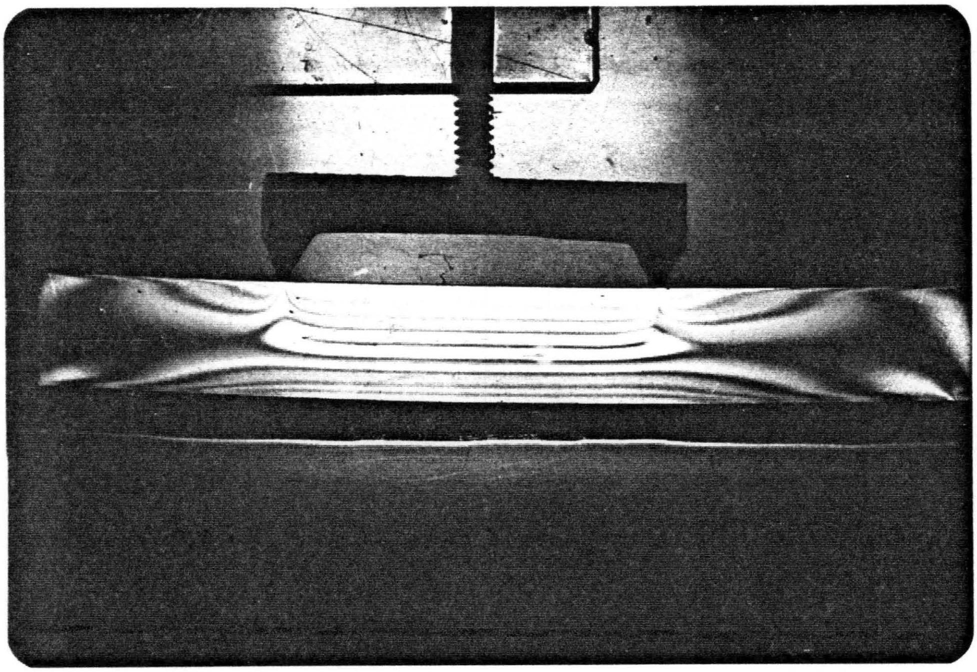


Fig.1-11. Pattern of fringes, in the beam under two concentrated loads, placed symmetrically.

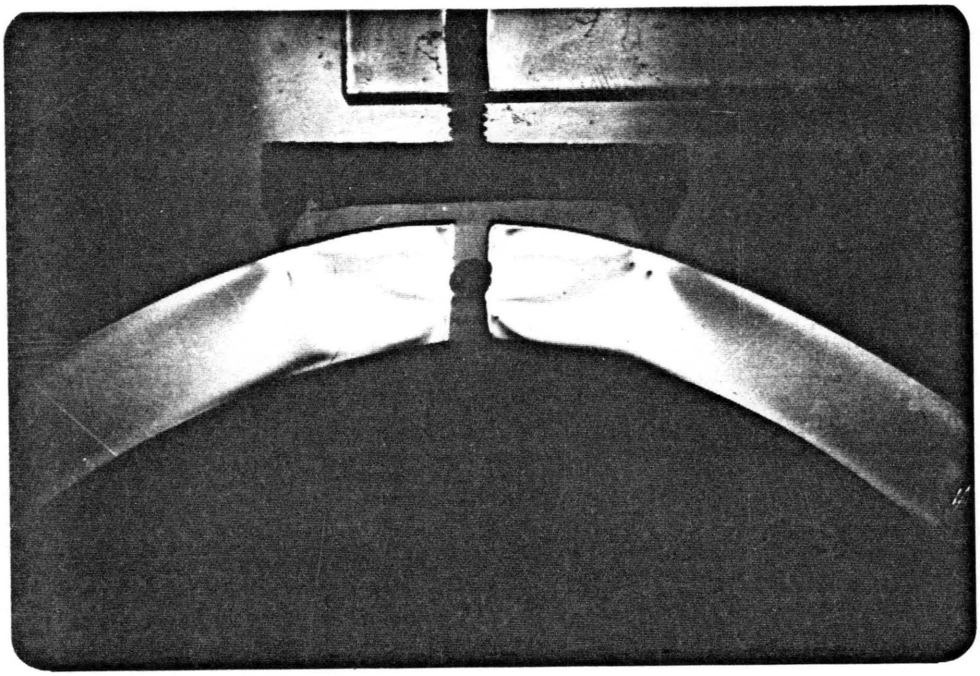


Fig.1-12. Pattern of fringes, in the three-hinged arch under two concentrated loads, placed symmetrically.

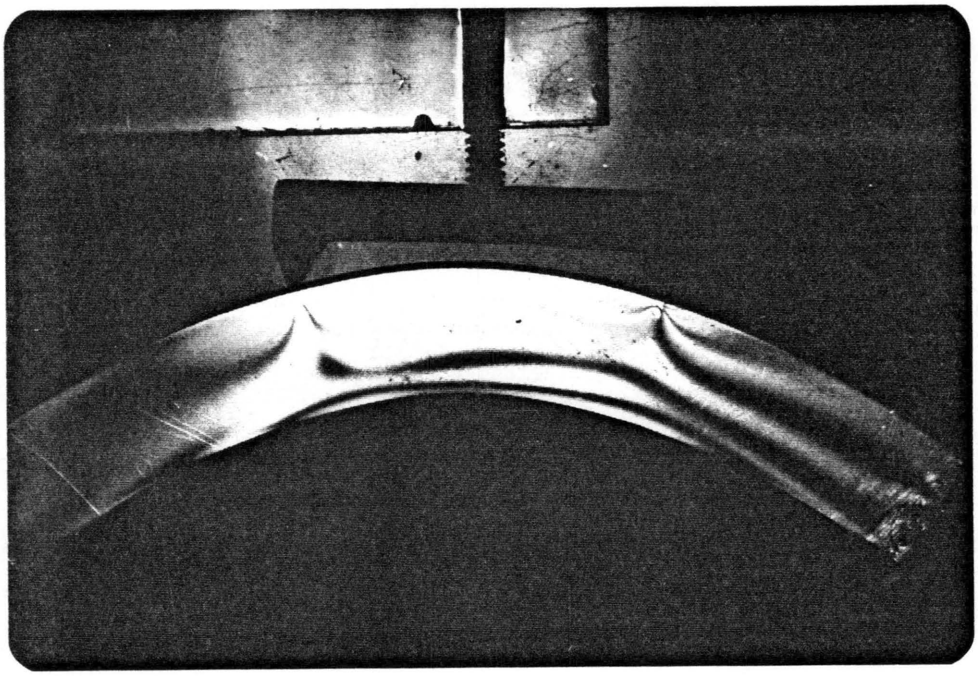


Fig.1-13. Pattern of fringes, in the two-hinged arch under two concentrated loads, placed symmetrically.

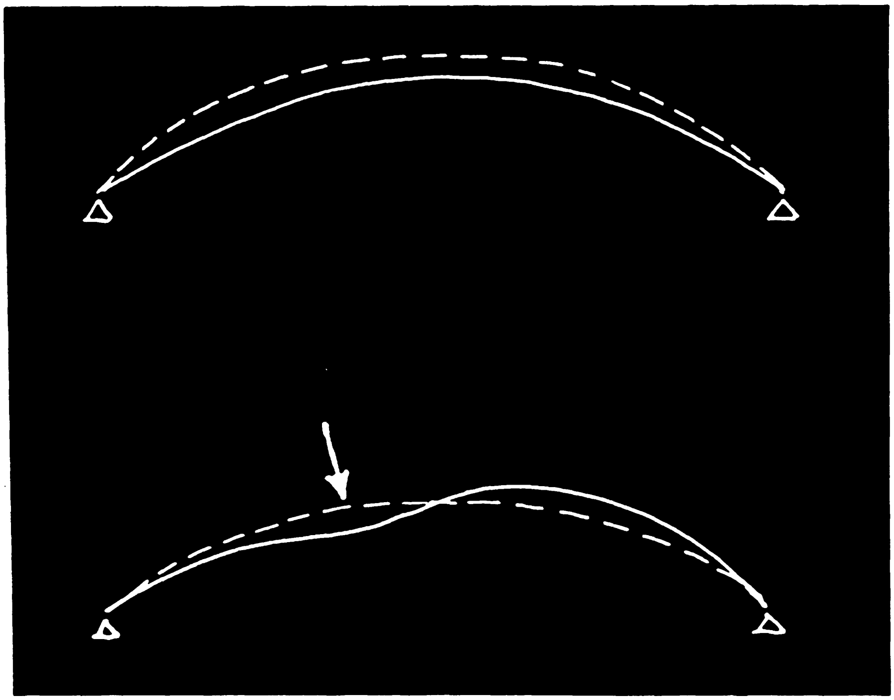


Fig.1-14. Two-hinged arch, under symmetrical uniform load, and under asymmetric concentrated load.

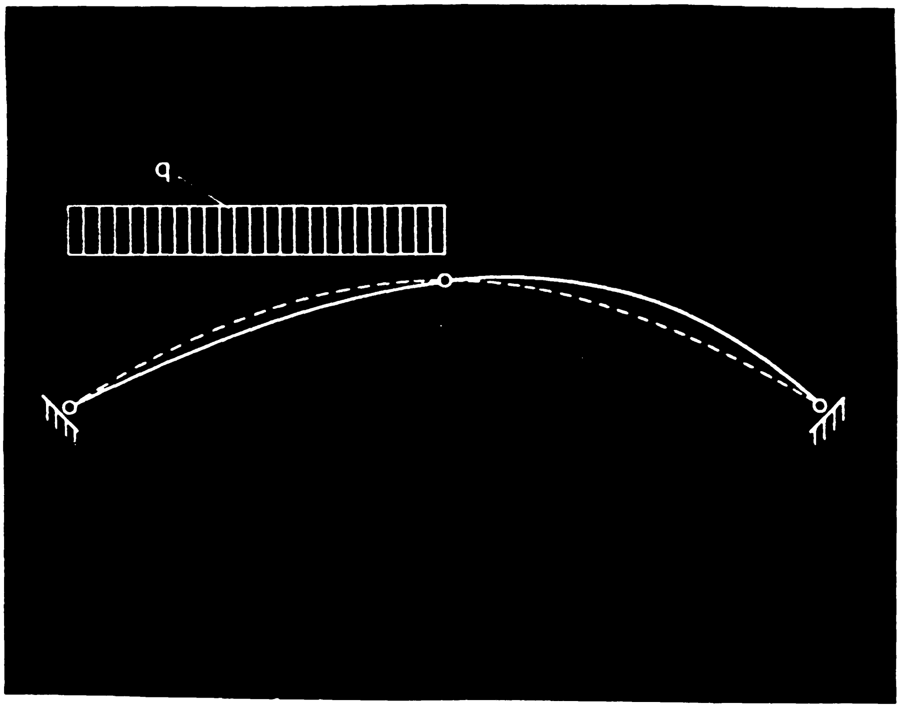


Fig.1-15. Three-hinged arch, under asymmetric uniform load.

on these huge churches by wind.

In their research, Mark and Clark used plane photoelastic models of the cathedrals, representing vertical cross sections of the constructions. By applying the loads (Fig. 1-18) to the heated model and then cooling it down, it was possible to freeze the strains, and consequently fix the photoelastic phenomena in the models, even if the loads had been removed.

A good understanding of principal stresses is a crucial problem in arch design. Even if we generally analyze building construction as exposed to bending, shear and longitudinal forces, we find that pure bending, shear or compression seldom exists alone. We would like to design arches for compression only, and of course, in reality compression may prevail. We must not forget, that at the same time, due to the lateral forces exerted by wind, non-uniform settling of the foundations, thermal expansion and contraction etc., the pattern of loading, and construction responses, may be much more complicated.

In the classical method of design, two simplification systems are generally presumed to determine deflections and stresses:

1. An assumption of the most probable loads and load patterns, and
2. A consideration of bending, shear and longitudinal forces as separate factors. A combination results in obtaining approximate values of stresses.

However, the need for precise and detailed calculation often does not exist, especially for minor constructions (unless they are repeated in long series of prefab processes), or if the data for design are approximate, or even uncertain.

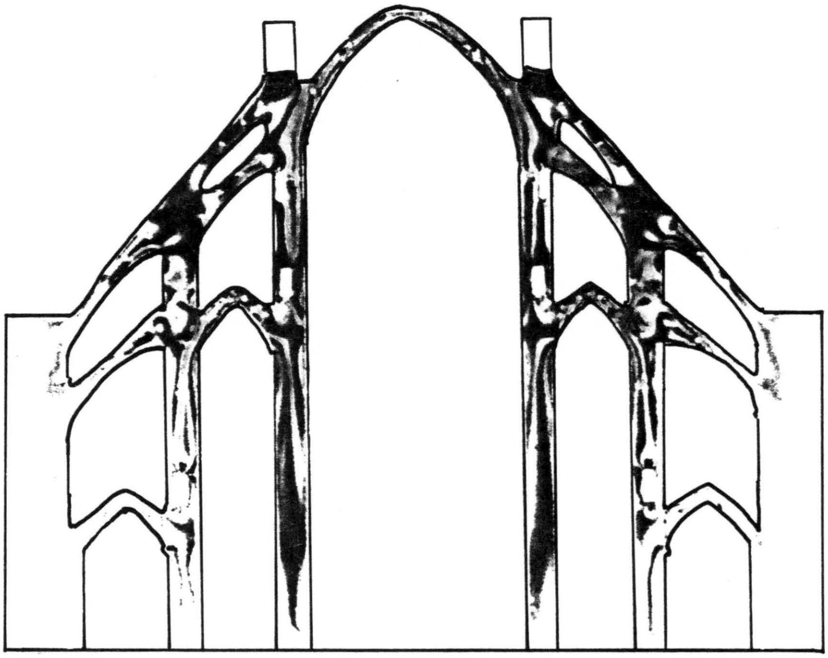


Fig. 1-16. Pattern of fringes in a photoelastic model of Bourges Cathedral, France.

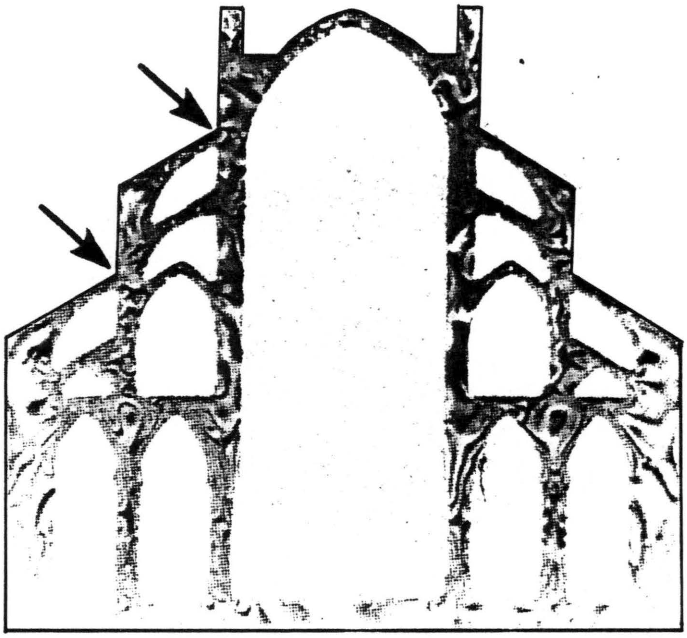


Fig.1-17. Pattern of fringes in a photoelastic model of the Cathedral of Notre Dame de Paris.

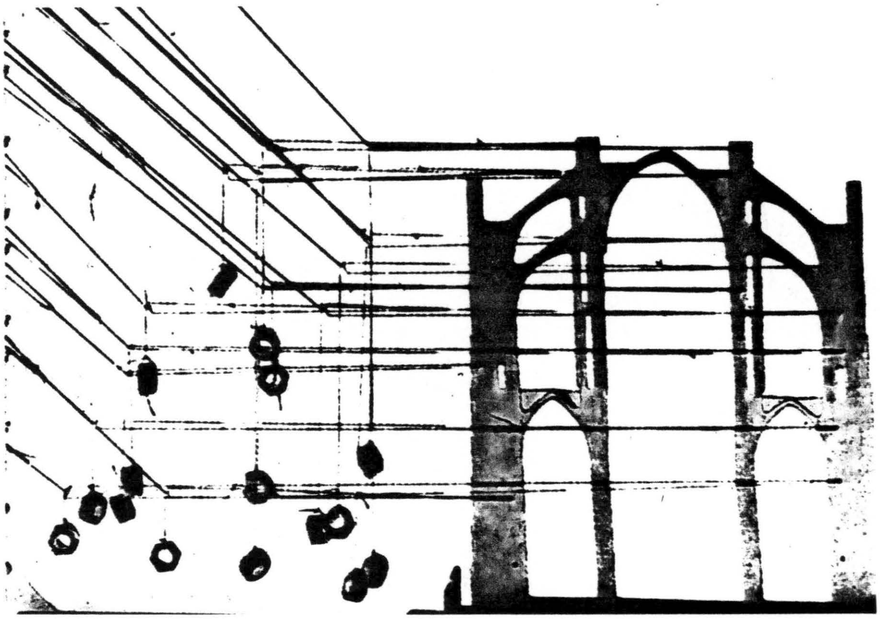


Fig.1-18. A testing model of the Amiens Cathedral.

The wires, in tension, imitate wind loads, occuring in reality.

1.3. METHODS OF CALCULATIONS.

For a long time, in designing arches the calculations have been considered to be difficult. This has been partly due to the fact that, except for three-hinged arches, arches are statically indeterminate. The equations describing a geometrical shape, the deflections as well as internal forces in such arches, are comparatively complicated. Before computers were introduced any even simplified procedure of the design process had not given easy and toil free solutions.

When I studied Civil Engineering in the '50s, special projects on arches terrified the students, and Bresse and Morsch equations with all their transformations were never forgotten. Even if we used Gaus' iteration method, there were no means to control intermediate phases of the calculations, and the final results often provided unpleasant suprises.

For centuries, simple and small arches have been built according to conventional patterns. More complicated and bigger arches have been solved with the help of diagrammatical methods and pilot scale tests.

1.3.1. Three-hinged Arches.

An analysis of these arches is straightforward, since they are statically determinate. We have four unknowns: two vertical components of forces A and B and two horizontal components of those forces. Four equations we have at our disposal, i.e. sum of all forces projected on XX axis equals zero; sum of all forces projected on YY axis equals zero, and sum of moments about the point A or B equals O. The fourth equation is a sum of moments about C, which also equals zero.

In case of symmetrical uniform loading q, a span of the arch = L, and rise = f, horizontal support reactions are each

$$H = \frac{qL^2}{8f}.$$

Bending moment in any point determined by co-ordinates x, y

$$M = 0.5\ q\ x\ (L-x) - H\ y.$$

Thus, for parabolic arch, described by equation: $y = 4fx(L-x):L^2$

$$M = 0.5\ q\ x\ (L-x) - \frac{qL^2}{8f}\,\frac{4fx(L-x)}{L^2} = 0.$$

for circular arch: $y = \sqrt{x(2r-x)}$, or $y = \sqrt{x(L-x)}$

$$M = 0.5\ q\ x\ (L-x) - \frac{qL^2}{8f}\sqrt{x(L-x)} = 0.$$

When A and B are known, the bending moment M, axial force N, and shear V can be found at any point by means of sections (Fig. 1-20).

$$N = P_x \cos\theta + P_y \sin\theta.$$

$$V = P_x \sin\theta - P_y \cos\theta.$$

θ - can be determined in any point, from

$$\tan\theta = \frac{dx}{dy}.$$

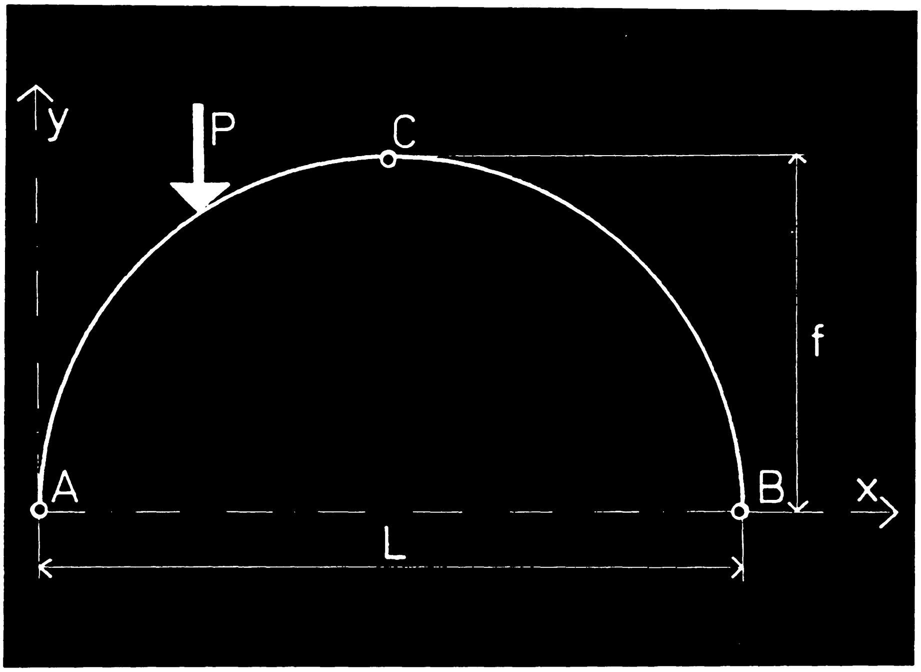


Fig.1-19. The three-hinged arch.

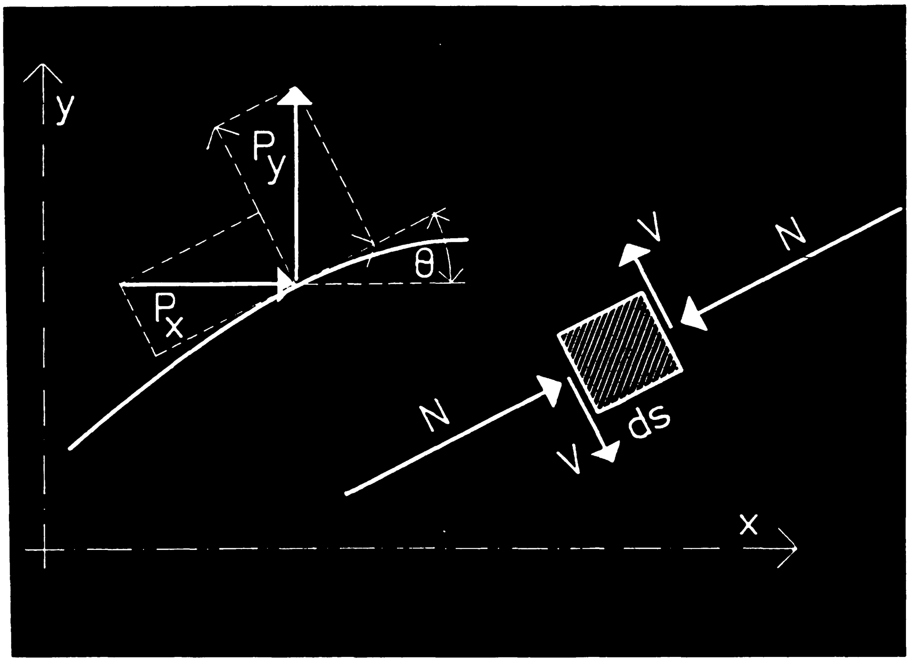


Fig.1-20. Forces in the three-hinged arch.

1.3.2. Two-hinged Arches.

A two-hinged arch is a statically indeterminate structure. The hinges at the supports, even if they can rotate, are immovable in both the vertical and horizontal directions, so both component forces of the reactions are unknown. Since we have only three equations of statics at our disposal, the redundant reactive force can be determined from the additional equation upon consideration of the deformation of the arch.

According to the classical solutions, the procedure is following:

We assume that the arch is symmetrical and symmetrically loaded. This means, that both vertical components of forces at A and B, i.e. A_V and B_V, are equal, and can be easily determined. The condition of symmetry simplifies the problem further, since both horizontal components of forces at A and B: A_H and B_H (often called the thrust of the arch and described as H), are equal.

To calculate H, we consider deformation of part CB of the arch, assuming that cross section C is fixed.

We consider, first, the vertical displacement of B u_{BV}, assuming that only B_V is acting and B_H does not exist. Then, we consider the action of a unit horizontal component force (the real value is not yet known and we want to determine it) causing displacement u_{B1}.

The displacement caused by H is H-times bigger

$$u_{BH} = H\, u_{B1}.$$

Since the hinge makes any displacement, except rotation, impossible

$$u_{BV} + u_{BH} = 0.$$

$$H = -u_{BV} : u_{B1}.$$

The displacements are calculated under several assumptions -- i.e. that the cross-sectional dimensions of the arch are small, when compared to the radius of curvature and overall length of the arch, which makes it possible to use formulas derived for a straight bar, with relevant simplifications based on the hypothesis of plane cross section.

$$u_{BV} = \int_0^{\frac{s}{2}} \frac{M(f-y)ds}{EI} - \int_0^{\frac{s}{2}} \frac{N\cos\phi ds}{EA}.$$

and

$$u \quad = - \int_0^{\frac{s}{2}} \frac{(f-y)^2 ds}{EI} - \int_0^{\frac{s}{2}} \frac{\cos^2\phi ds}{EA}.$$

where:

f - the rise of the arch

s - the length of the center line AB

(we integrate from B to C, i.e. from 0 to s/2)

E - modulus of elasticity

I - moment of inertia of the cross section

A - area of the cross section

ϕ - the angle, that the tangent to the center line, at the point, makes with the x-axis

M - bending moment

N - axial force

y - coordinate of the center of the particular cross section.

If, for instance, our arch is of parabolic shape, described by equation $y = 4fx(L-x):L^2$; $A = A_0:\cos\phi$; and $I = I_0:\cos\phi$, where A_0 and I_0 -cross section and moment of inertia at the crown of the arch, and the load q is uniformly distributed along the horizontal projection of the arch

$$M = \frac{q}{2}\left(\frac{L^2}{4} - x^2\right).$$

$$N = [B_v - q(\frac{L}{2} - x)]\sin\phi .$$

$$H = \frac{qL^2}{8f}\,\frac{1}{1+\beta}.$$

where

β - numerical value depending on the propotions of the rise to span (f : L).

It is often necessary to calculate deformations due to temperature changes. In the symmetrical arch, as considered above, the thrust value caused by a uniform temperature change

$$H = -\frac{\alpha t L}{2 u_{B1}}.$$

where

α - the coefficient of thermal expansion

t - the increase of temperature by t degrees

u_{B1} - theoretical displacement of the hinge B, caused by a unit horizontal force applied at the hinge (as in Fig. 1-21).

1.3.3. Hingeless (Fixed) Arches.

A hingeless arch (Fig. 1-22) is three times indetermined statically, i.e. it represents a structure with three redundant quantities.

In a symmetrical arch, if we determine the bending moment, shear and axial forces at the crown, we can consider the half of the construction like a cantiliever, neglecting the second half of the arch. For three additional equations (needed for problem solving) we find the

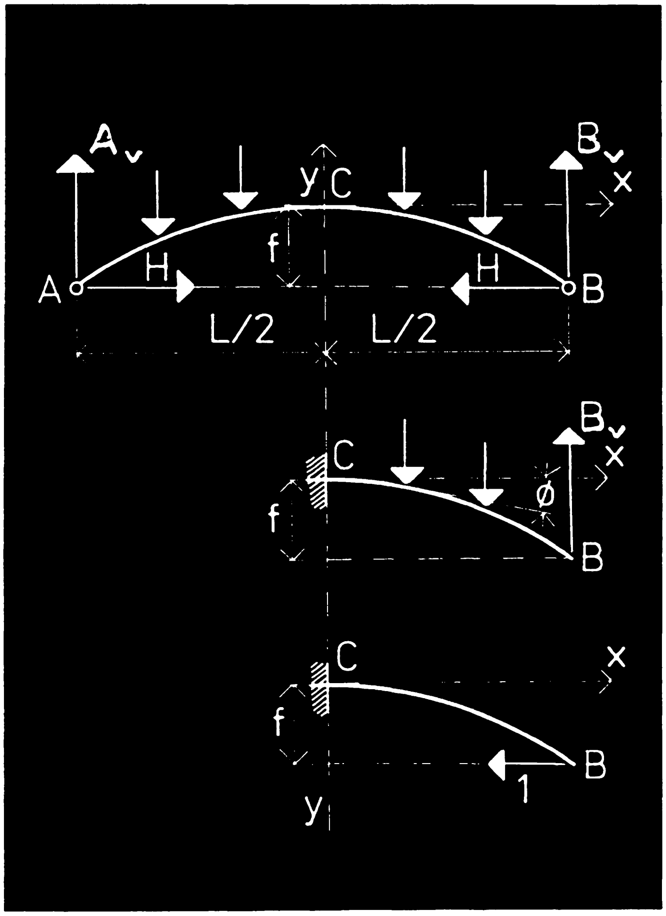


Fig.1-21. The two-hinged arch.

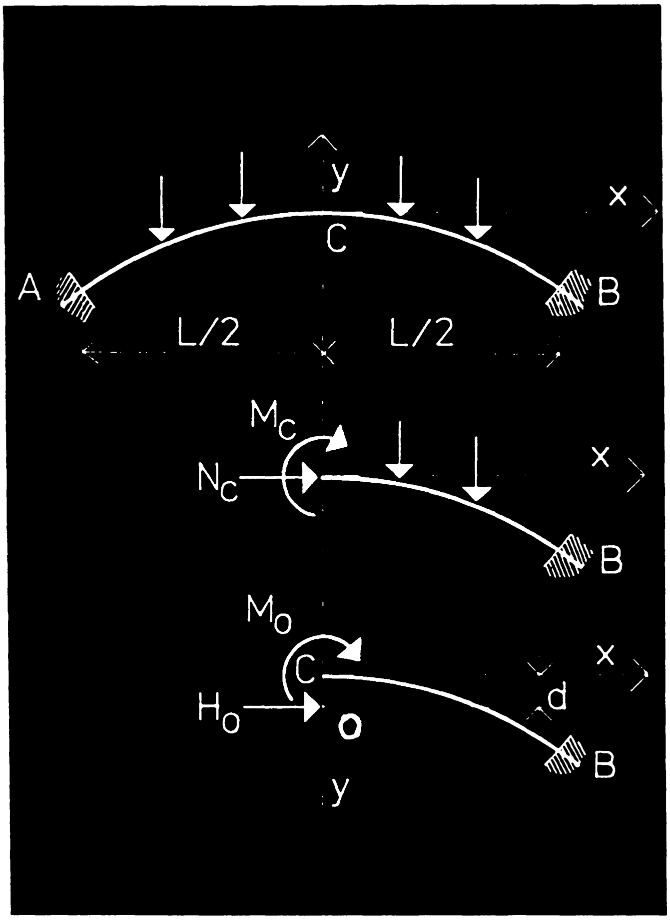


Fig. 1-22. The hingeless arch.

Two unknowns M_c and H_c , since the shear in the case of a symmetric load vanishes in the crown. O - elastic center.

deformations of a chosen cross section at any point, i.e. the vertical and horizontal deflections, and the rotation of the said cross section.

If the arch is asymmetrical, we take as the redundant quantities the bending moment, and the two components (horizontal and vertical) of the reaction, at the left or right hand support.

For practical structural design, it is convenient to use tables with values of bending moments, shear and axial forces for the particular type of arch. Semicircular and parabolic arches, loaded symmetrically or under typically distributed loads were solved a long time ago, and are quoted in textbooks and engineering aids.

1.3.4. Procedure of Numerical Calculation of Redundant Quantities.

The determination of redundant quantities requires the evaluation of integrals for assumed extension

$$d = \frac{u_d}{\theta_d} = \frac{\int_0^{\frac{s}{2}} \frac{y\,ds}{EI}}{\int_0^{\frac{s}{2}} \frac{ds}{EI}}.$$

for condition that the point at the crown, under uniform load, does not move laterally

$$\int_0^{\frac{s}{2}} \frac{My\,ds}{EI} + \int_0^{\frac{s}{2}} \frac{N\cos\phi\,ds}{EA} - d\int_0^{\frac{s}{2}} \frac{M\,ds}{EI} + H_o\left[\int_0^{\frac{s}{2}} \frac{y(y-d)ds}{EI} + \int_0^{\frac{s}{2}} \frac{\cos^2\phi\,ds}{EA}\right] = 0$$

and the cross section does not rotate

$$\int_0^{\frac{s}{2}} \frac{M\,ds}{EI} + M_o\int_0^{\frac{s}{2}} \frac{ds}{EI} = 0.$$

As for the uniform change in temperature

$$-\frac{\alpha t L}{2}+H_o\left[\int_0^{\frac{s}{2}}\frac{y(y-d)ds}{EI}+\int_0^{\frac{s}{2}}\frac{\cos^2\phi ds}{EA}\right]=0.$$

If we have a equation describing the curve, as in the case of a parabola, or a semicircle, the integrals can be readily evaluated. However, very often architectural design deals with a variety of forms, difficult or impossible for mathematical interpretation and clear projection. In such cases, only systems of ordinates can be given.

For an approximate calculation of integrals, the arch should be divided into a finite number of segments, and the integration should be replaced by a summation.

It is interesting to remark here, that the excessive number of subdivisions does not necessarily increase correspondently the accuracy of the results. Very often, division into 16 parts will do, with an error not exceeding 1 per cent.

The arch shown in Fig. 1-23 exemplifies the procedure. The required distance of the elastic center is marked with d.

For the summation we register all the parameters from the above mentioned equations like Δs (for ds); b, h (width and height of the particular cross sections); I (moment of inertia of the sections); $\frac{\Delta s}{I}$; y; etc. From the summation parameters (from the last equation), we calculate thrust, produced by the temperature change. The other redundant quantities can be calculated in the same way, from remaining equations.

The influence lines of H, N and M provide the visual and most convenient illustration of the results (Fig. 1-24).

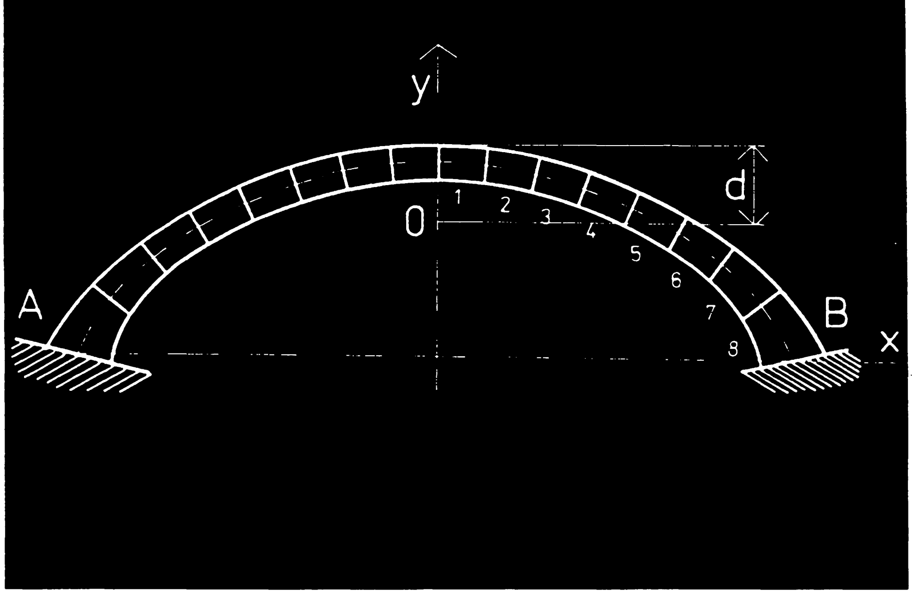


Fig.1-23. The division of an arch into eight (sixteen in total) portions for calculation by the approximate method of summations. (The finite number method).

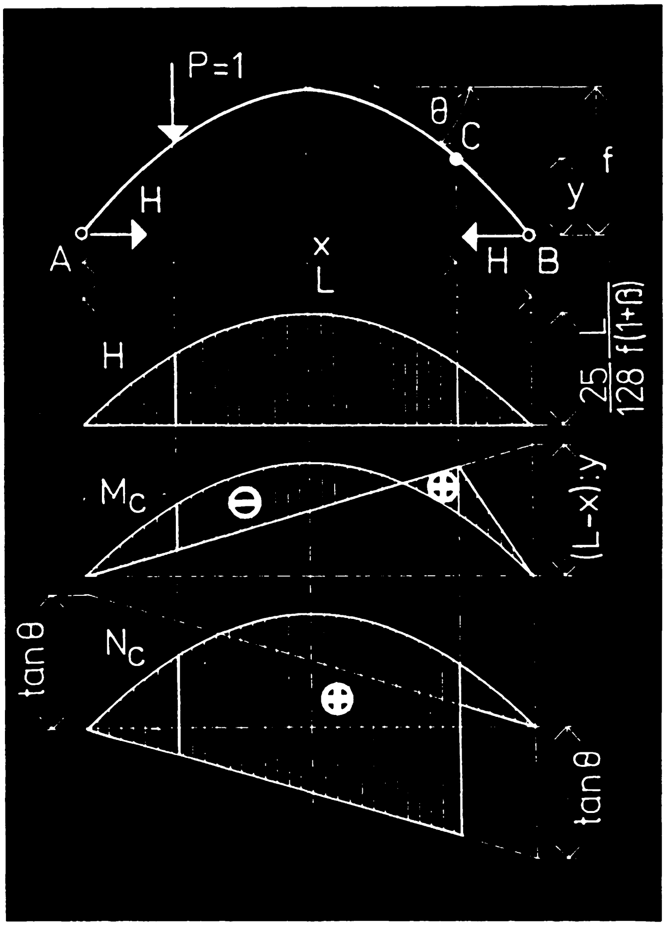


Fig.1-24. Influence lines of thrust (H), bending moment (M_c) and axial force (N_c) for point C (x,y) in two-hinged parabolic arch $y = 4fx^2 : L^2$.

1.4. STRUCTURAL FORMS.

Arches may be classified according to various characteristics:

From the point of their STATICAL WORK - types of arches are:

A. Single span arches
  - Three-hinged arch
  - Three-hinged arch tied
  - Two-hinged arch
  - Two-hinged arch tied
  - Fixed or hingeless arch
  - Fixed at one end, with a hinge at another end

B. Continuous arches

From the point of GEOMETRY:

A. Symmetrical
  - Circular
  - Funicular
  - Parabolic
  - Elliptical
  - Hyperbolic
  - Other geometrical forms

B. Asymmetrical or irregular

From the point of SHAPE:

  - Jack and sham
  - Flat (segmental)
  - High (high relationship f:L)

From the point of <u>STIFFNESS:</u>

- Massive
- Slender

From the point of <u>CONSTRUCTION:</u>

- Simple arches, with rectangular, circular cross sections
- Box-shaped arches, I, V, etc.
- Vaults with and w/o ribs, circular, coved, groined, etc.
- Domes with and w/o ribs
- Shells
- Truss-type arches
- Mixed systems, in combination with suspention, etc.

From the point of <u>MATERIAL:</u>

- Stone
- Brick
- Wood
- Concrete
- Reinforced concrete
- Pre- and post-stressed concrete
- Steel
- Aluminum
- Other materials

A number of examples of different structural forms are given in figures 1-25 to 1-44.

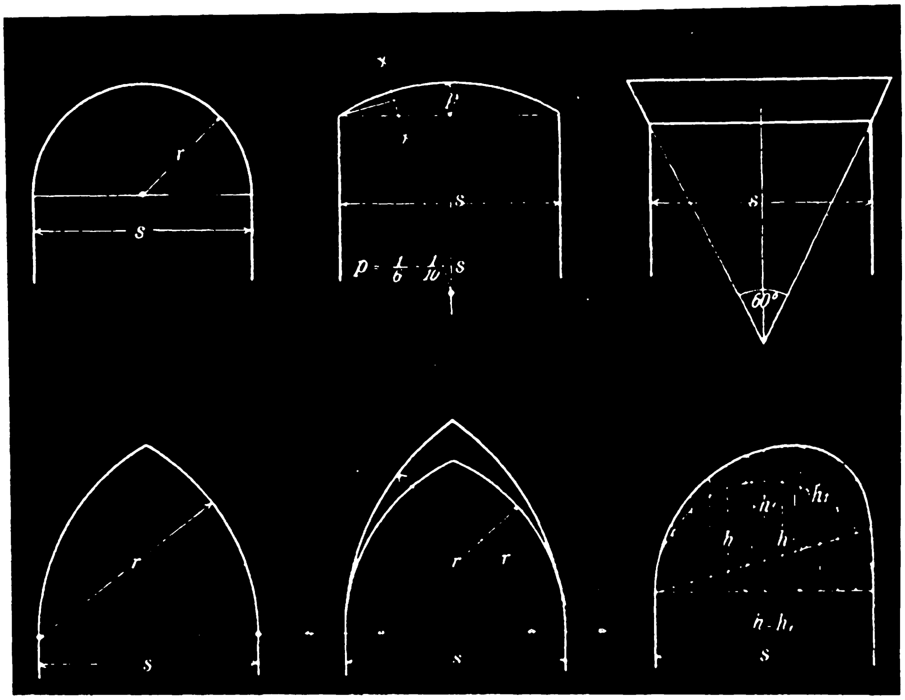


Fig.1-25. Basic geometrical shapes of arches.

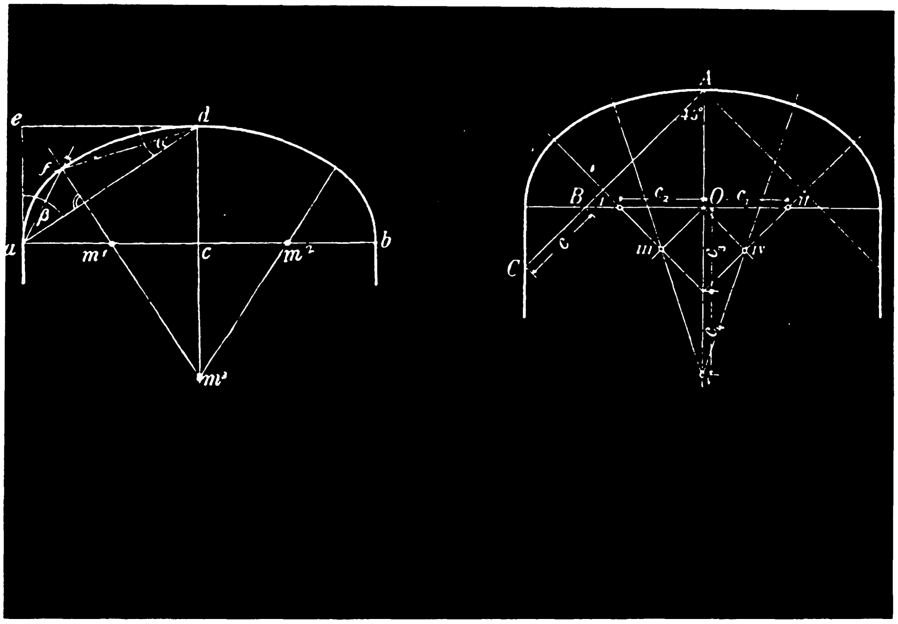


Fig.1-26. Geometrical construction of the elliptical arch.

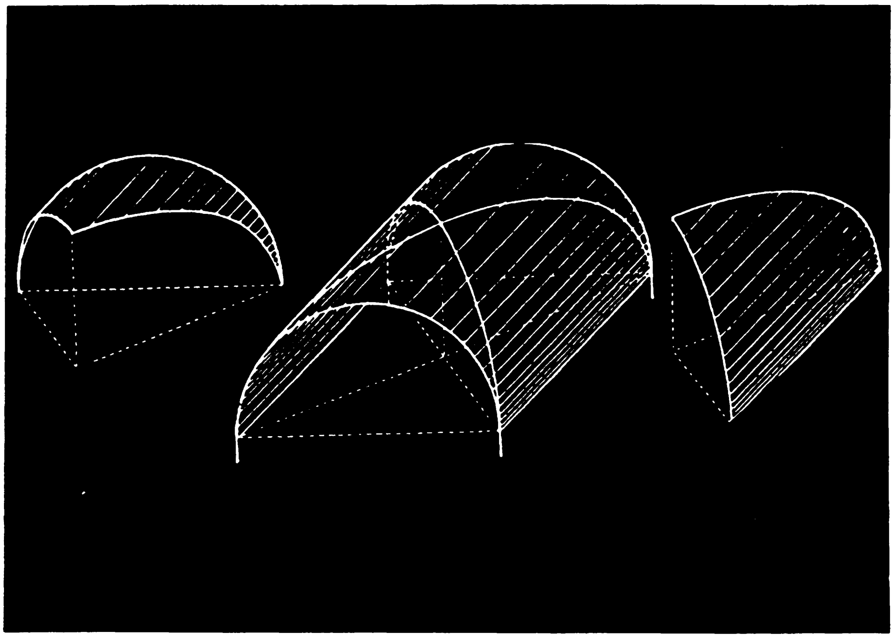


Fig. 1-27. Cylindrical vault, and construction of coved vault.

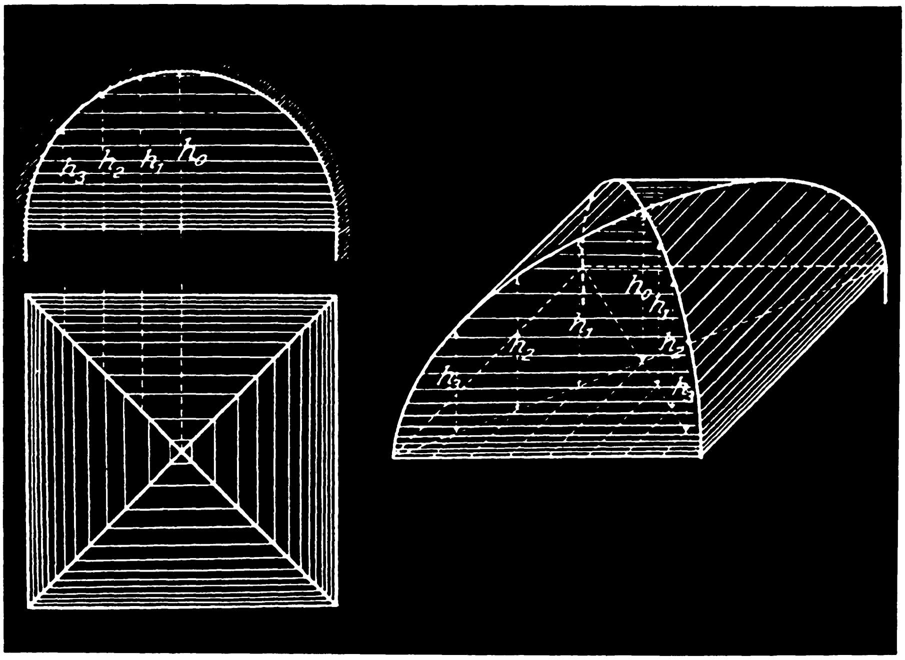


Fig.1-28. Coved vault construction.

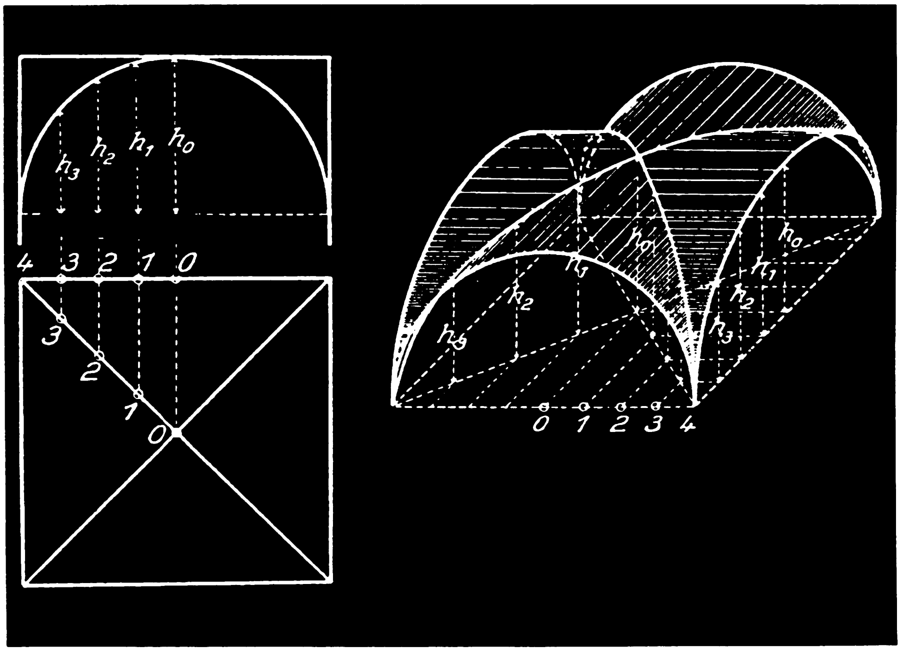


Fig.1-29. Cross vault construction.

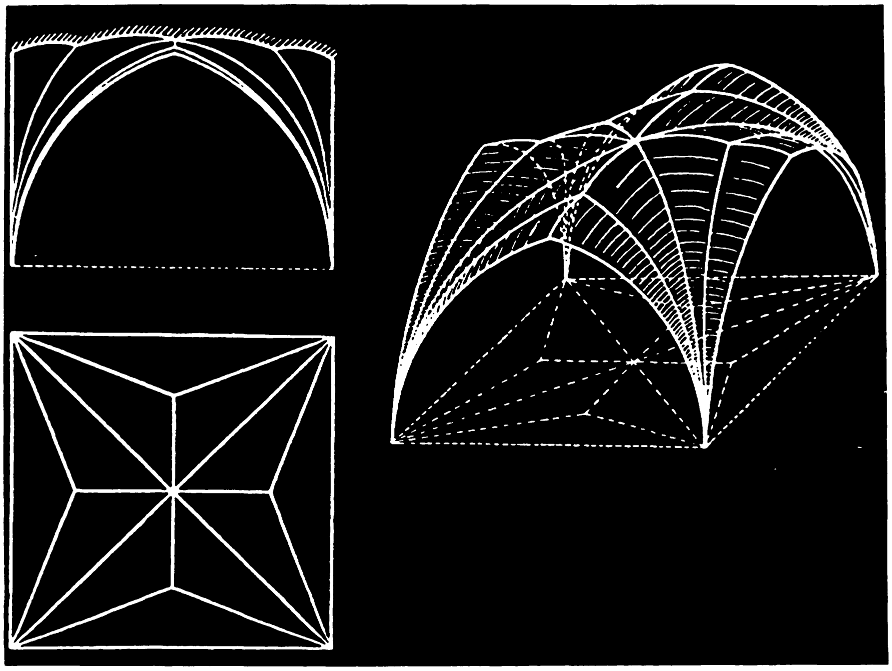


Fig.1-30. Groined, Gothic vault.

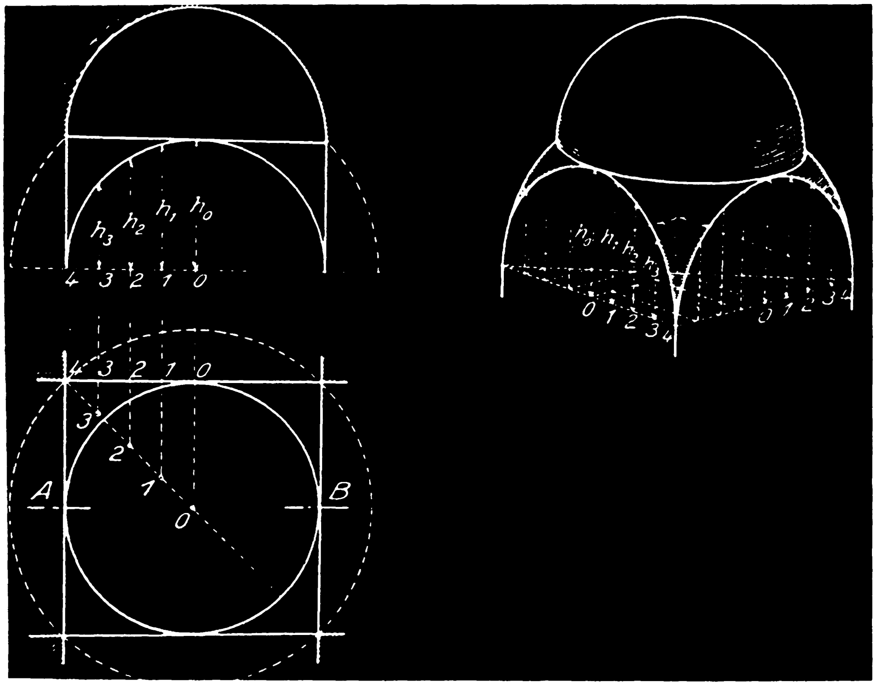


Fig.1-31. Construction of the domical vault with a dome.

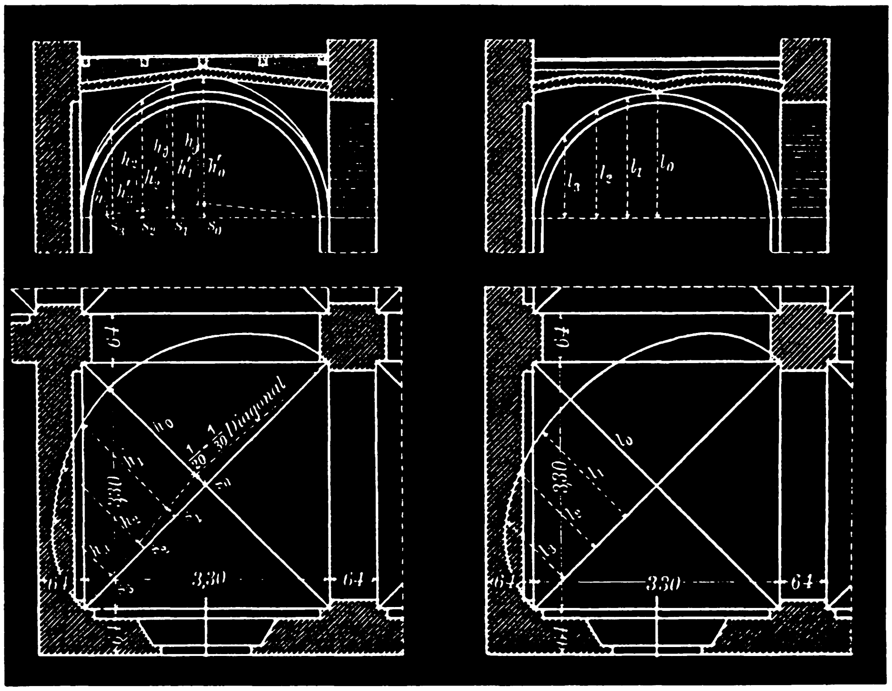


Fig.1-32. Coved vault over a square room.

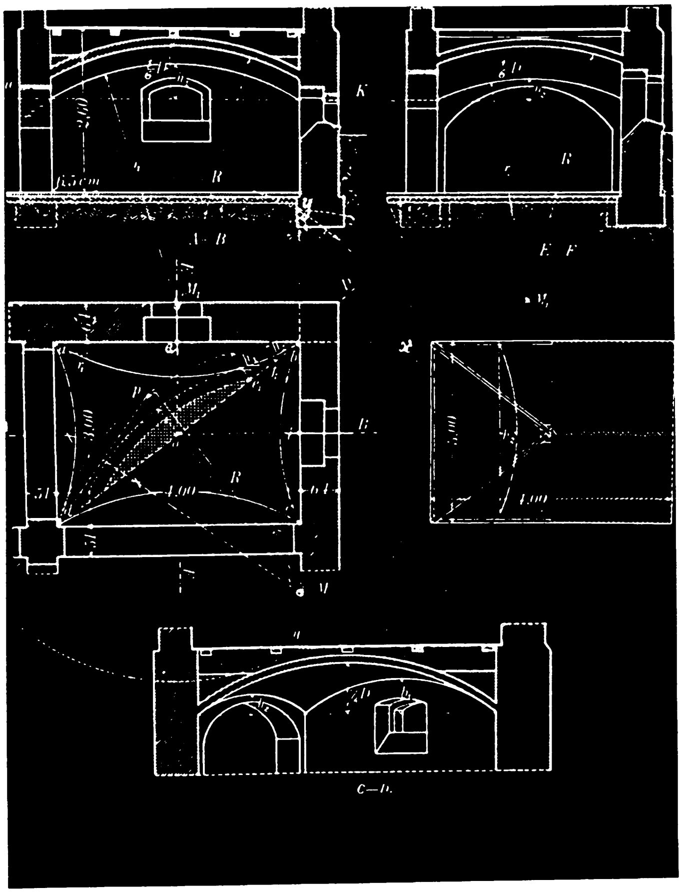


Fig.1-33. Coved vault over a rectangular room.

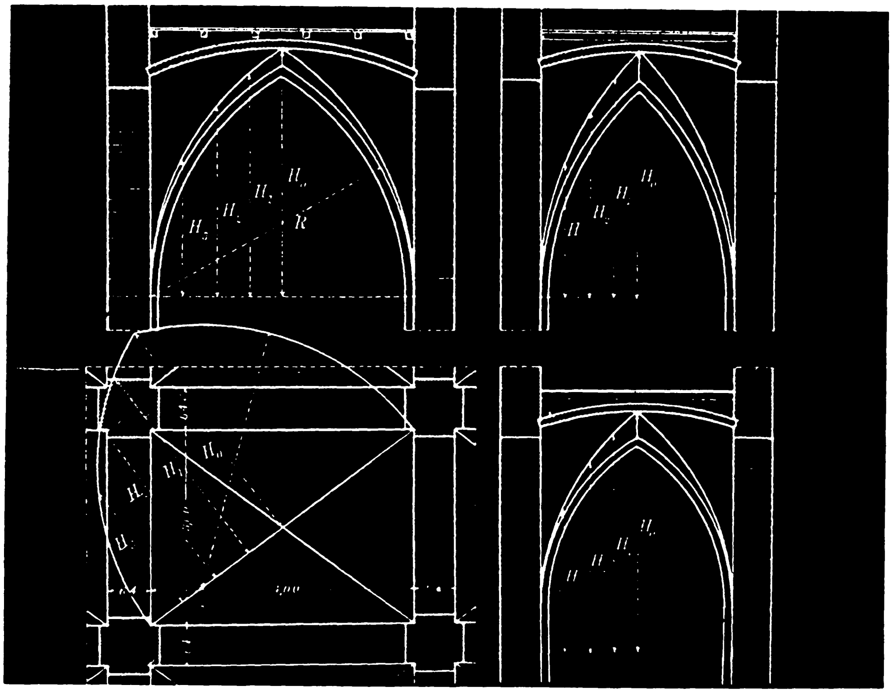


Fig.1-34. Pointed (Gothic) vault over a rectangular room.

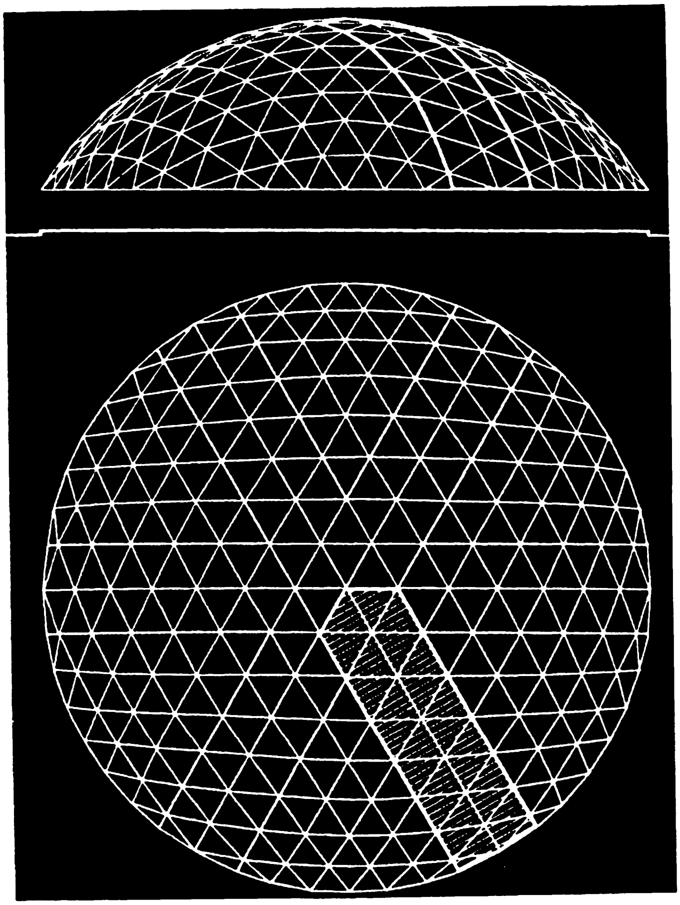


Fig.1-35. Construction of the geodesictype dome.

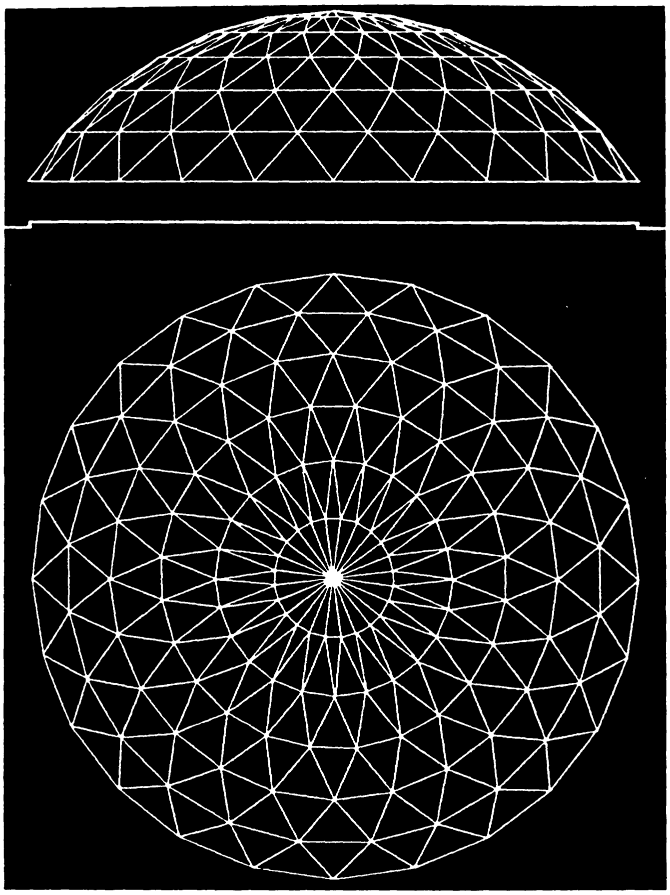


Fig.1-36. Construction of the dome with horizontal rings.

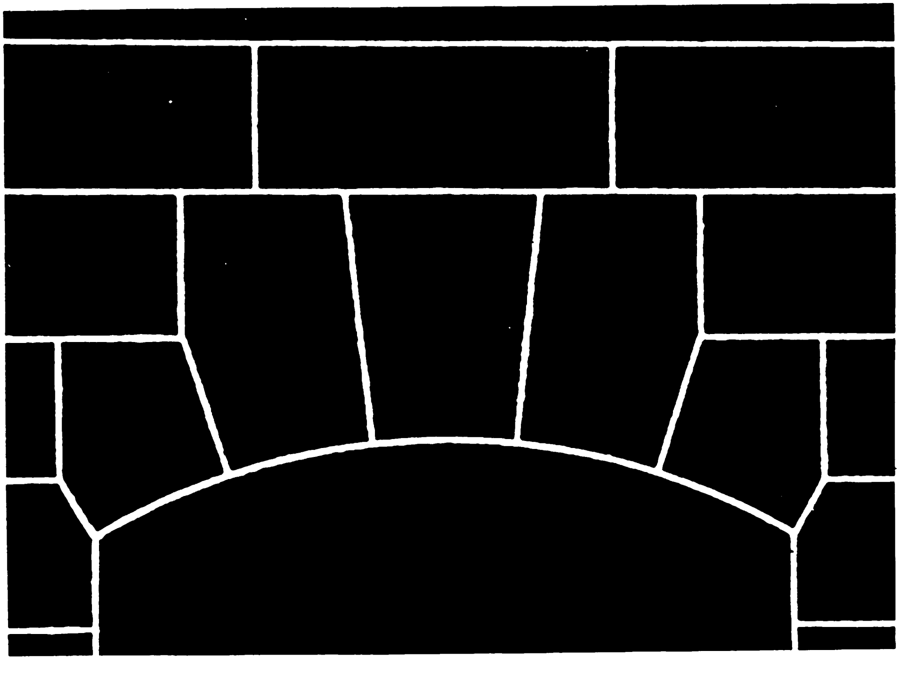


Fig.1-37. Segmental arched lintel with a keystone.

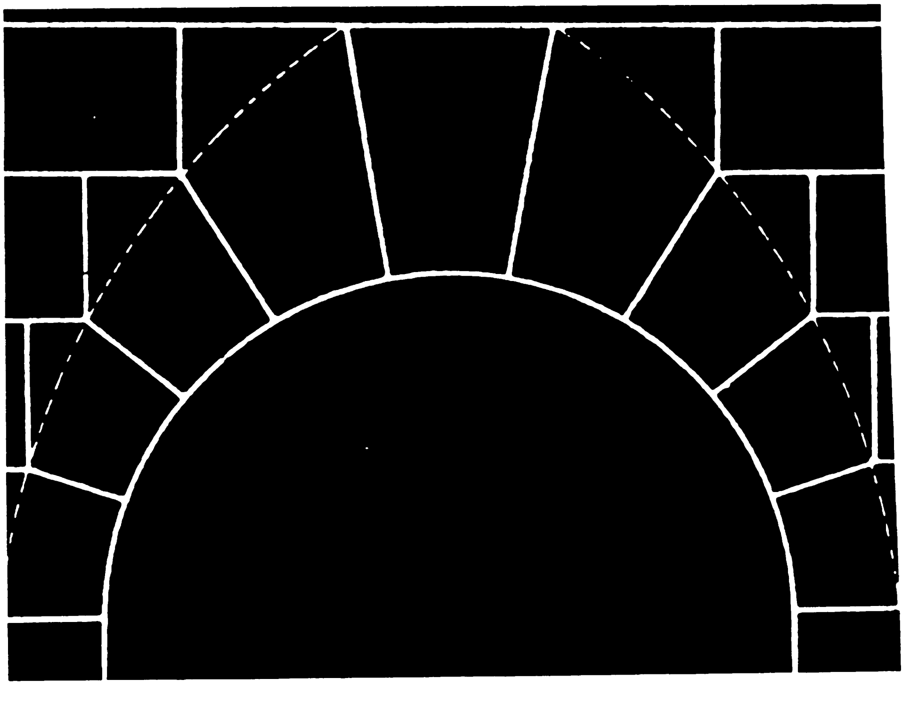


Fig.1-38. Semicircular intrados arched stone lintel.

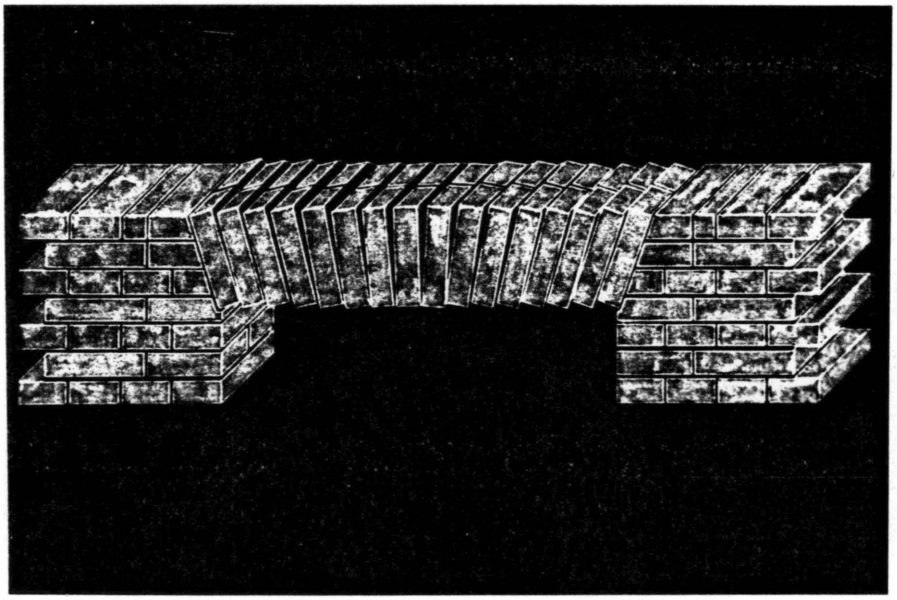


Fig.1-39. Brick jack arch.

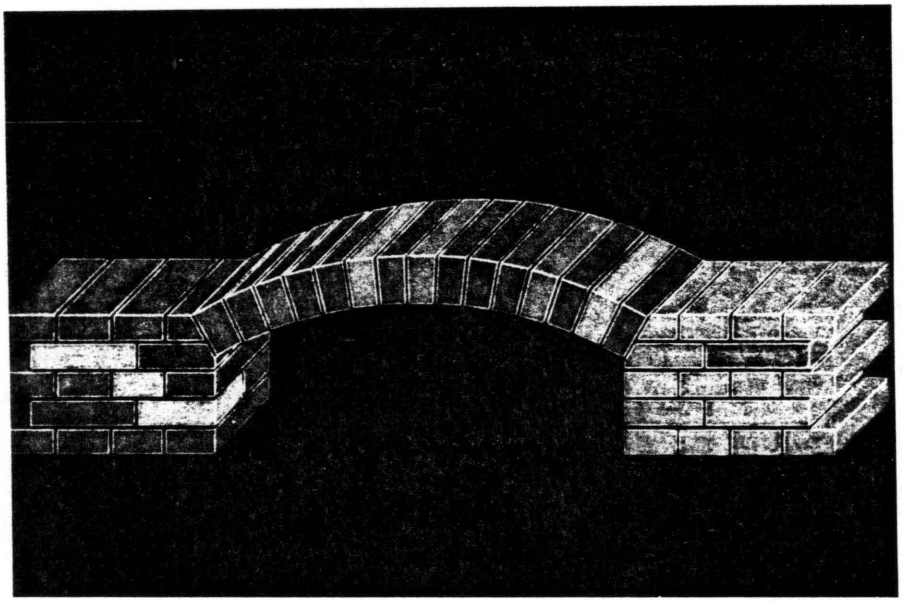


Fig.1-40. Simple brick archway.

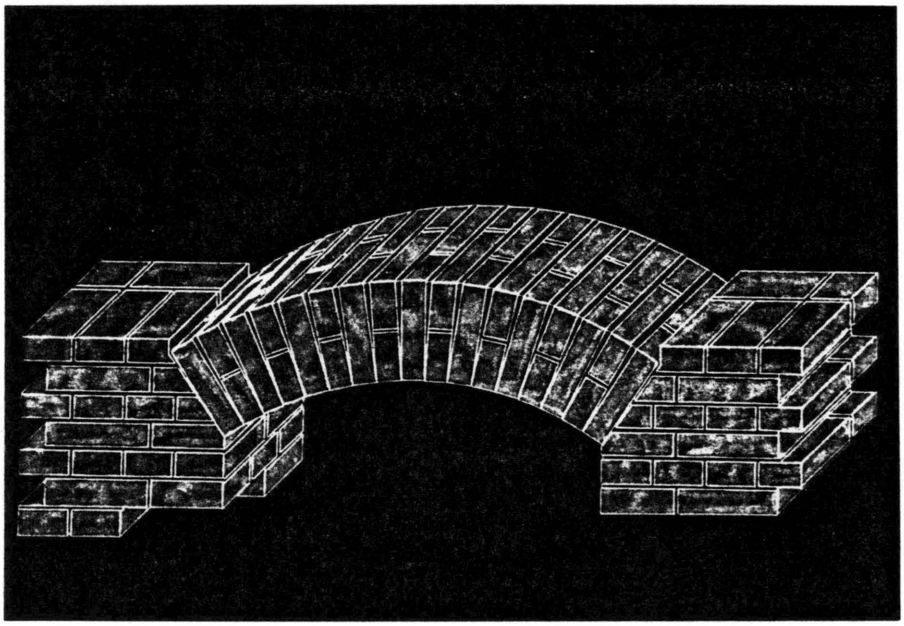


Fig.1-41. Brick archway.

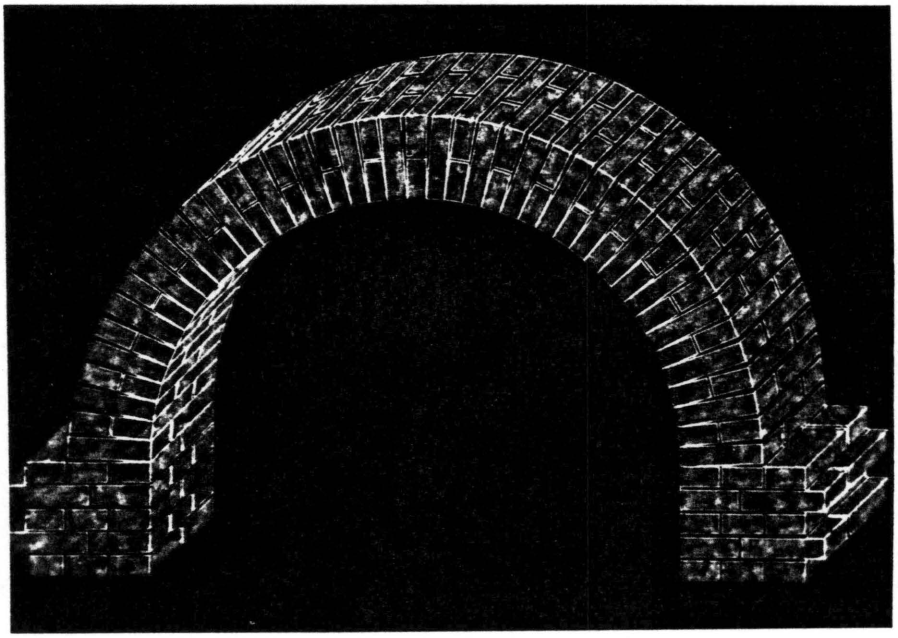


Fig.1-42. Semicircular brick arch over a bigger span.

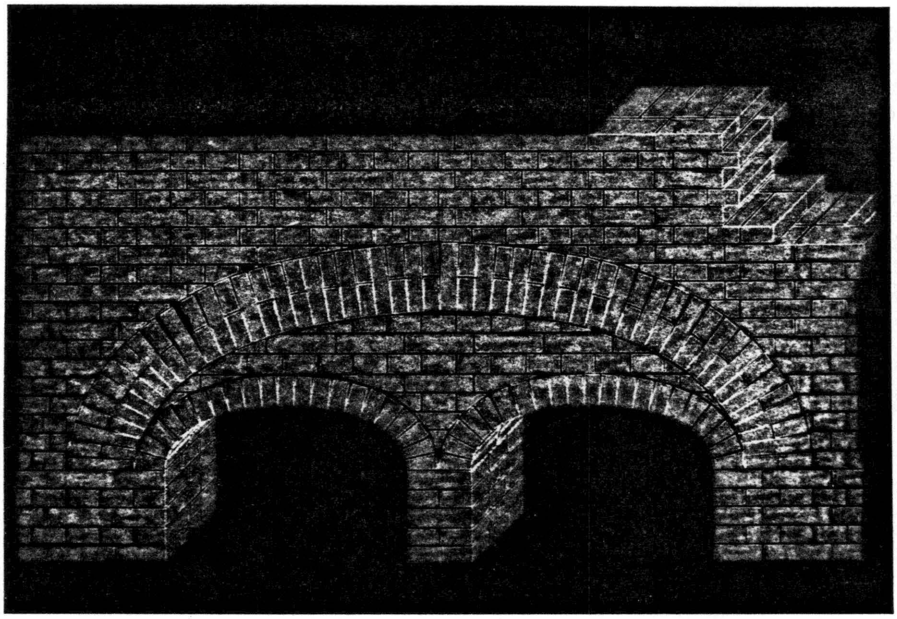


Fig.1-43. Relieving arch.

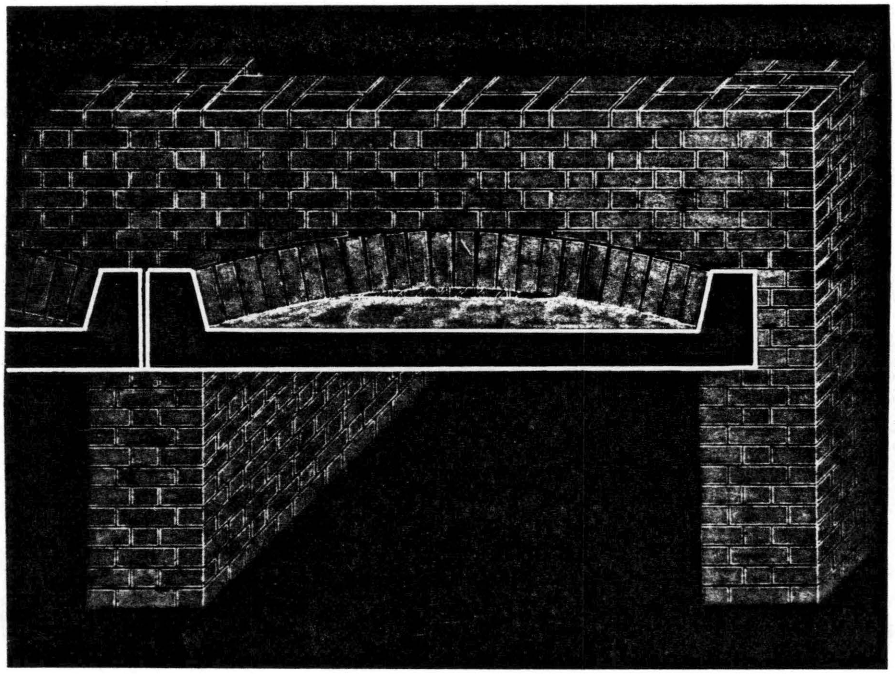


Fig.1-44. Arch with a reinforced concrete tie.

1.5. OPTIMAL SHAPES OF ARCHES.

In the architectural practice, the choice of a shape of arch is often crucial.

It is taken for granted that a parabola makes the best curvature for arches. Indeed, if we make an experiment with two arches, made of separate wooden elements imitating masonry units, one of them shallow (Fig. 1-45), and the second full semicircle (Fig. 1-46), they seem to prove this opinion. In the first arch, we see openings between particular elements occuring at the bottom of the crown. In the second arch, openings occur at the supports, and in the middle, on the upper surface of the arch.

If we draw a parabolic axis representing a predicted line of resultant compression forces (in figures 1-45 and 1-46 marked with an arrow), we see that the openings happen exactly in places where they should have been expected. However, in reality, arches are exposed to different loads, often nonuniform and asymmetrical, changing in time and dynamics. In these cases some other shapes of arches may better fulfil specific construction demands.

There are different methods of approach in design. The simplest procedure, involves comparative analysis of well known curvatures -- for instance, parabolic, funicular etc. and elimination of the worst. Another traditional approach means the choice of a shape most suitable for the construction based on experience, and often on engineering intuition. After the preliminary decision, the designer introduces gradual improvements of the shape, based on analysis of bending,

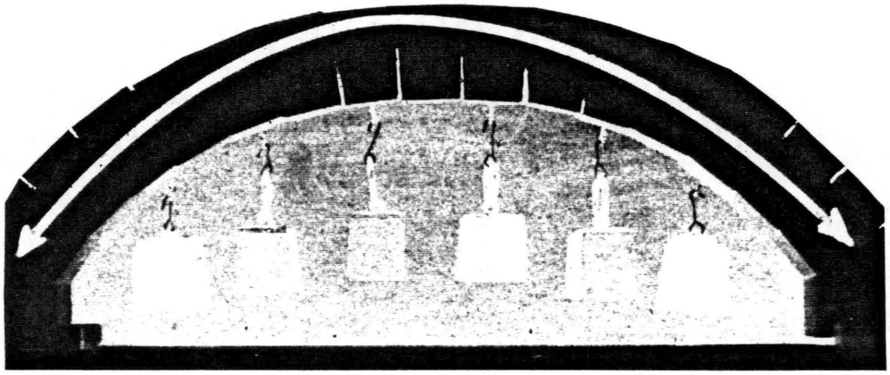


Fig.1-45. Test model of the shallow arch under uniform load.

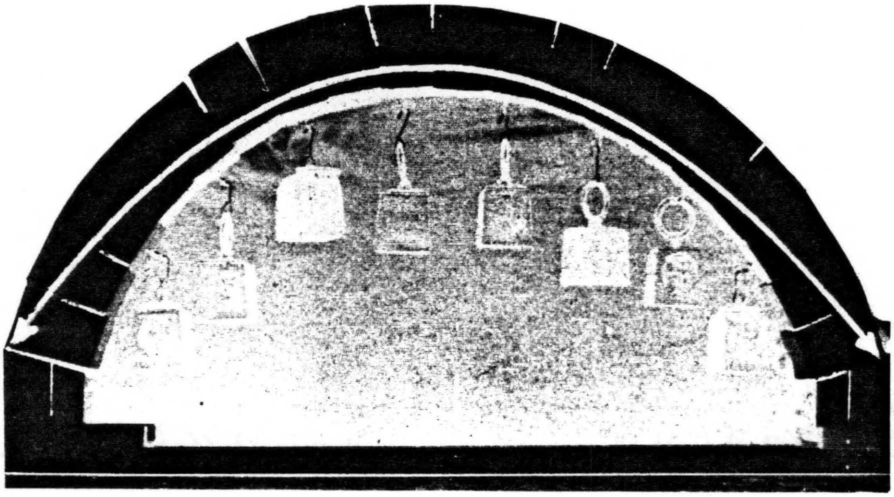


Fig.1-46. Test model of the semicircular arch under uniform load.

shear and axial forces. Photoelastic and other models may be of great help here.

In speaking about construction decision making, we do not discuss the cases where aesthetic and functional factors determine the shapes and features of buildings and structures.

New developments in scientific structural design are especially suited for design of arches. The application of computers makes it possible to combine simultaneously optimization of geometry and cross sections.

The calculations are generally based on elastic analysis (the force, or flexibility method), in which redundant forces are chosen as the unknowns. Also often the displacement, or stiffness method is used, in which restraints are added to prevent movements of the joints, and the forces required to produce the restraints are determined.

Plastic analysis of arches supplements elastic analysis, providing useful information about the collapse load.

Using this procedure, the optimization proceeds in two separate design areas. One is the area of cross section variability (or in the case of arched truss, member-size variation). The other is variable of geometric shape of the arch. A general flow diagram of the procedure is shown in Fig.1-47.

Symbols applied in Fig. 1-47:

α - is a scalar multiplier,
required to minimize Z in direction $\{s\}$.

q - iteration number

p - number of independent coordinate variables

Z - represents volume (or weight) of arch or truss.

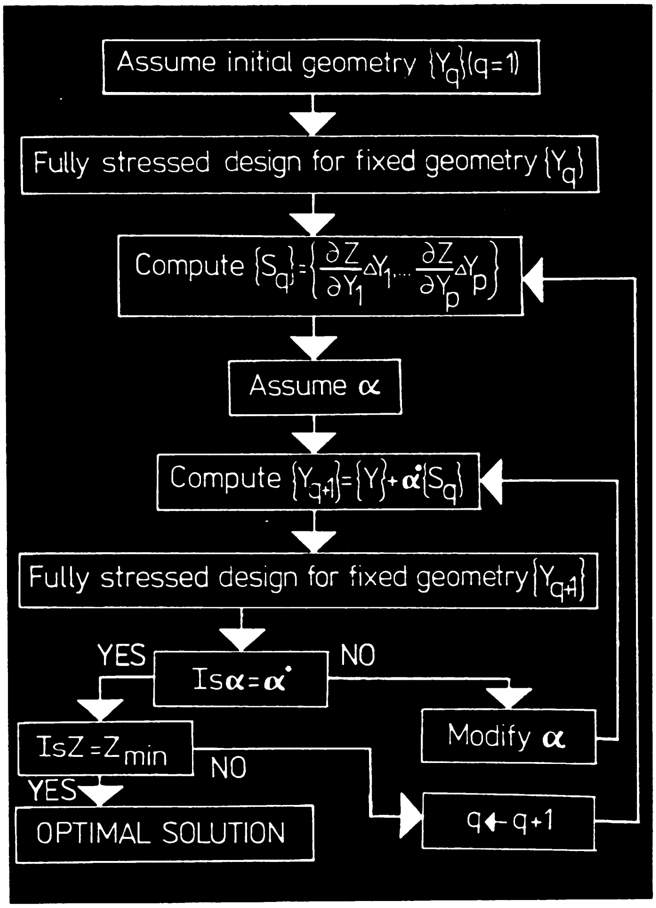


Fig.1-47. An example of optimization procedure.

Geometrical flow diagram, solution in separate design spaces.

Designers of structural arches have ready-made procedures at their disposal.

Four American engineers [5] have worked out the numerical bending analysis of arches. The procedures have been described for the elastic analysis of arches by large deflection, second order, and classical theories.

The axial strains and temperature effects have been considered. As a result of the analysis, moments, axial loads, and displacements can be evaluated at division points. The procedure gives high accuracy with few divisions (compare chapter 1.3.4.). An application of computers makes the whole design process fast and inexpensive.

A practical application of modern structural design may be illustrated with the design of the world's longest span arched bridge, built by United States Steel, over the New River Gorge in West Virginia, and opened in 1977.

Having in mind depth of the canyon (the height of the roadway had to be kept 267 m above water), the designers decided to assume a span-to-rise ratio at 4.6 : 1. This meant corresponding dimensions: a span 518.16 m, and a rise 112.78 m (Fig. 1-48).

The fixed-type arched truss, with both top and bottom chords anchored, was assumed in the preliminary phase of the design. This configuration was discarded, when analyses showed that the bottom cord of the arch would carry most of the applied loads, at the anchorage.

A two-hinged arch seemed more appropriate, but it took a number of calculations before designers discovered that only by locating the pin in the middle distance between the chords could they ensure effective load

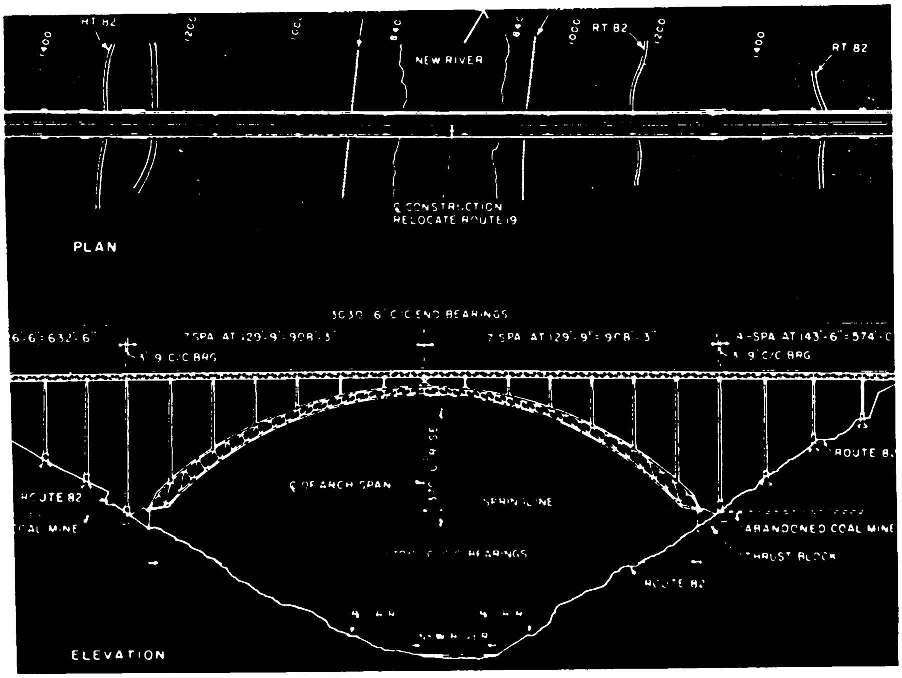


Fig.1-48. New River Gorge Bridge.

Its fine shape designed as a result of optimization study.

transmission over the entire length of the arch.

The designers, relying on the common opinion that there is no better shape for an arch than a parabola, applied that curve. This produced a situation where the position of the resulting dead load thrust line was highly erratic. However, using this thrust line as a guide, other geometric patterns were tried. Finally, a five-centered series of circular arcs was found to be the best fit to the thrust line.

After selecting the basic shape of the arch, and arranging of truss members, the engineers analysed a number of load combinations. Twenty six different distributions of uniform live load were considered in combination with six concentrated live loads. Special bracing was applied, to provide resistance to wind forces. To determine all member forces for a concentrated unit load, applied at one bent, the STRESS computer program was used. Repeating the process, for the unit load at each bent in turn, produced data for the mathematical influence line diagram of each member of the arch.

Maximal expected live load deflections for this bridge (a real achievement of contemporary engineering) are 159 mm (vertical), and 108 mm (longitudinal). Maximum transverse deflection due to wind loads is 523 mm.

The discussion on optimal shapes of arches has been concentrated on technical issues. From the point of construction we consider the strength and bearing capacity of an arch in question, the pattern of forces exerted on it, the changes and dynamics of loading. From the point of technology, specific demands of particular building materials are important; also, technical means for an erection of the construction have to be taken into account.

The construction and technological solutions have to meet demands of the economy, in so far as no individual, no city, no country has unlimited resources. But even if the designed construction fulfils demands of correctness of the construction, the up-to-date technology and economy, it must possess a human factor - architectural quality. In this aspect we can look for optimal solutions in terms of function, organization of space, circulation, and psycho-physiological comfort. Still there is the shape, color, expression, scale and a relationship to the environment. It is terrifying to think of the result, if mankind were to follow a course, having only optimization in mind.

2. HISTORICAL DEVELOPMENTS OF ARCH IN ARCHITECTURE.

2.1. ANCIENT TIMES.

The arch is a beautiful form; logical, pure and full of expression. Geometrically an arch is a curved beam, generally supported on both ends. We have been used to archways and arch constructions so much that we can hardly imagine buildings and engineering constructions without them. However, there were times when humans did not know arches and could not apply them for construction purposes.

The importance of the invention of the arch in building may be compared to the invention of the wheel in transportation. It turned out to be a great step in progress throughout the history of mankind. It enabled covering bigger spans with less building material and using materials available, especially stone and brick, in a more rational way.

We do not know when the first arches were built. Probably the very first arches with which man dealt with were those of the natural rock construction of caves.

The archeological discoveries have proven that in the valley of the Tigris and the Euphrates, as long as 60 centuries ago, the Sumerians built arched houses on the marshes (Fig. 2-1). Those houses were suited in hot and humid climate of Mesopotamia. They were light and strong, and through the gaps between reeds the necessary ventilation was provided. At the same time, the buildings protected inhabitants

Fig.2-1. Relief on the Sumerian vase.

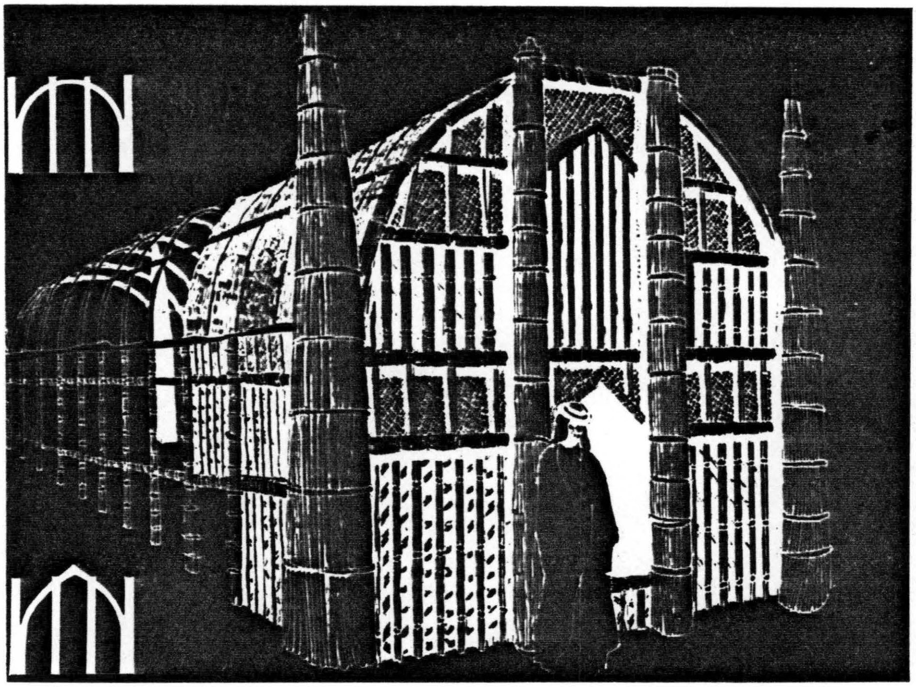


Fig.2-2. Construction of the contemporary house on the Euphrates marshlands.

against undesirable visitors: snakes and dangerous animals.

I will never forget the reception given by a leader of a tiny Arab village on the Euphrates marshlands accessible only by boat. We had been sitting on the floor and drinking strong Arab coffee from one small glass which circulated from hand to hand. We could admire the spacious and fascinating interior in the simplicity of its semi-barrel shape. The reeds formed a strong elastic vault in a natural parabolic shape. From outside, (Fig. 2-2), it reminded one exactly of a building carved on Sumerian vases of the First Dynasty of Uhr.

Since some of these buildings are considerably long, the front and rear walls fulfill the function of enclosure rather than serving as shear walls. There are no windows in the longitudinal arched walls. The entrance/exits are located in both the front and the rear walls.

The Egyptians in their monumental constructions first used the relieving arch over the rockcut burial chamber under Amenembet III's pyramid at Hawara. The engineers of the Egyptian pyramids always worried about how to relieve the tremendous weight of stones piled above the hollow spaces inside the structure. In the Cheops pyramid, for instance, they built 5 horizontal superimposed stone ceilings (stone megalith plates) which were supposed to carry all the weight. In fact two large granite blocks, (preceding and acting like future arch structures) placed obliquely above, carried the weight (Fig. 2-3). It should, nevertheless, be mentioned that even if the stone blocks were set without mortar the carefully shaped big pieces were set incredibly tight (mean distance between them not exceeding 1/4 mm) which provided necessary friction between the stones. This construction has

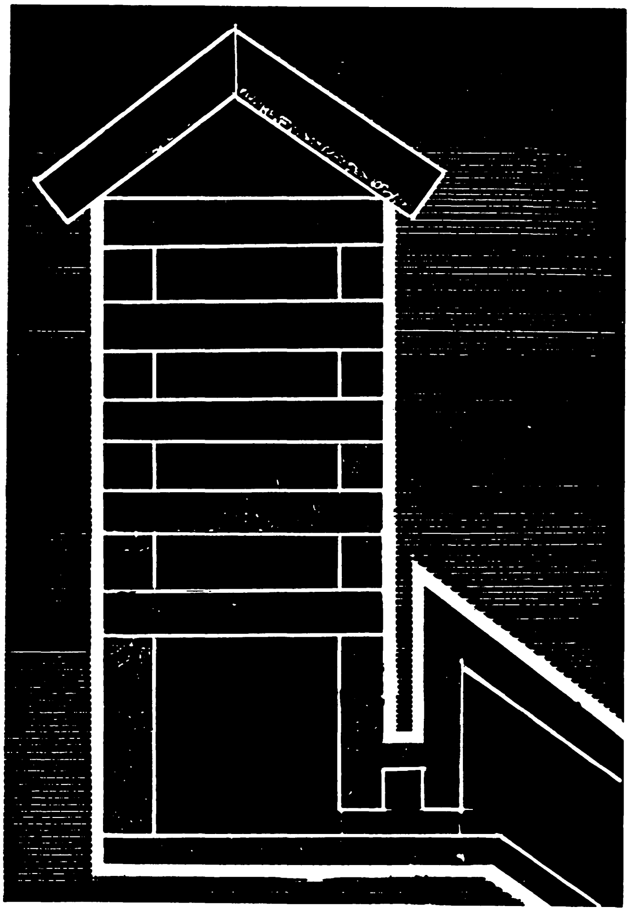


Fig.2-3. Pre-arched structure in the Cheops pyramid.

worked like contemporary lintels.

The invention of vaulting, the only method available for bridging long spans with stone and brick was, until recent times, assumed to be Roman. But Romans learned the art of vaulting from the Etruscans, who in turn learned it from the Greeks. Even if the contemporary archeological discoveries have confirmed the theory that the vault cannot be attributed to the Romans, they made great contribution to the development of vault. The bridge at Bieda, built as long ago as 500 BC, is still standing, and some other bridges survived the last world war even though they were exposed to heavy traffic of tanks and other armored vehicles exerting tremendous dynamic loads.

The Ancient Greeks used arches mostly for bridges. One can hardly find any arch in their imposing temples equipped with lines of columns and triangular porticos. The famous Lion Gate of Mycenae, considered by historians as one of the very first arches, is not simply an arch - but rather a beam with an inconstant depth (Fig. 2-4).

Many interesting structures may be found on Crete, once under Mycenaean hegemony. They, probably, owe their origin to the royal tombs in Uhr, and their form has survived untill today. The Treasury of Atreus at Mycenae, built with sawed stone blocks, forms a beehive shaped dome. After each course of stones was laid, the shaft was back-filled with tightly packed earth to take the lateral pressure. The construction over the entrance may be considered a prototype of an arch (Fig. 2-5). It was built in the same way as corbel arched entrances to the Uhr tombs. The tombs, like numerous buildings of Mesopotamia, have been constructed of sun dried clay bricks. The

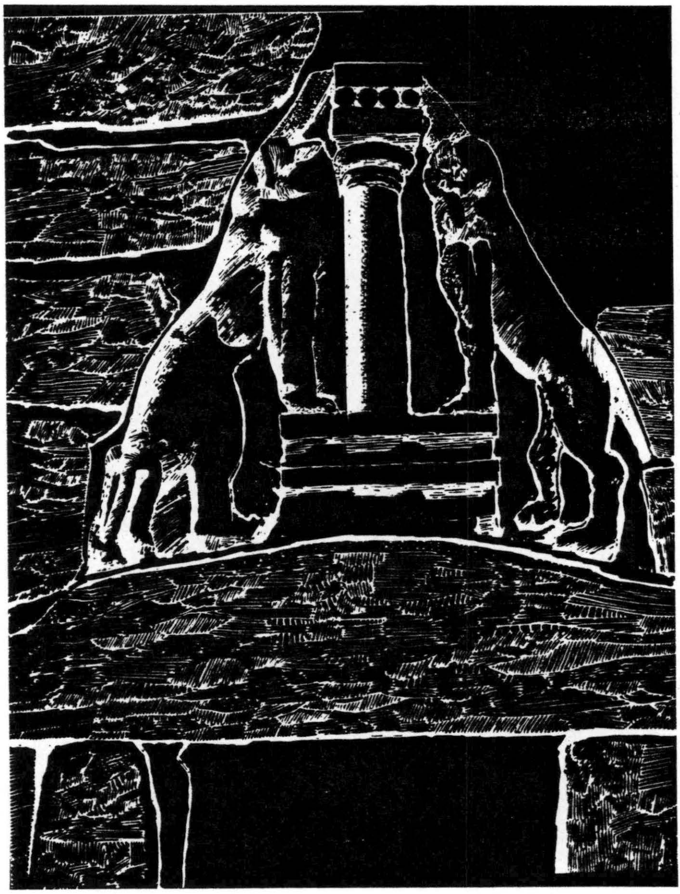


Fig.2-4. Lion Gate at Mycenae.

The beam of inconstant depth supports a tympanum.

The corbeled arch construction above is actually incomplete.

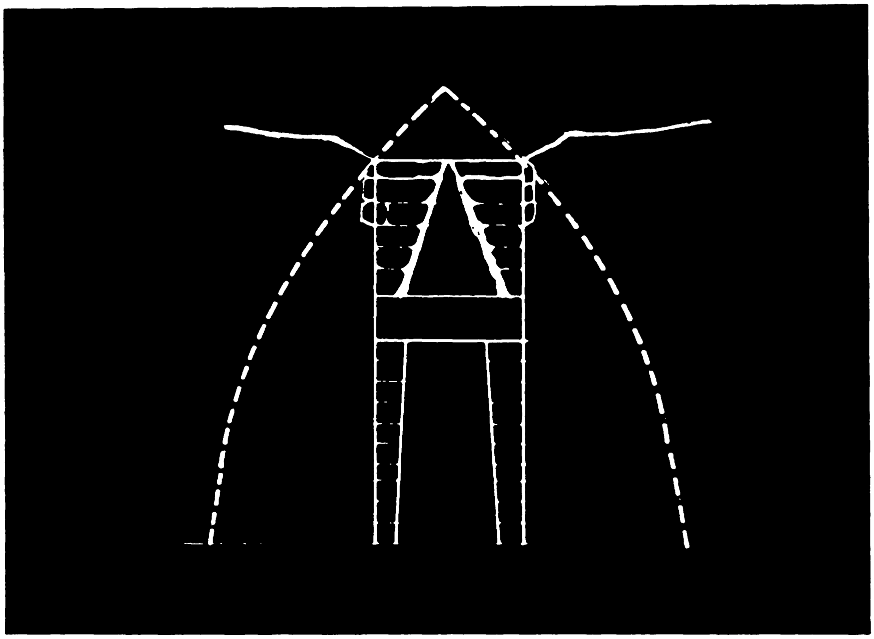


Fig.2-5. Stone corbeled arch, Treasury of Atreus at Mycenae. After erection, the inside corbels were chiseled smooth.

Sumerians came to know natural asphalt and how apply it for bonding.

The difference between Greek and Roman architecture lies in the extension of the use of arches by the Romans.

Even in a short outline one must mention the Pantheon, its magnificent domed structure 44.5 m in diameter, or the 30-meter vaulted roof over the hall of the palace of Diocletian.

The Romans used mostly semicircular arches, which as is well known, have considerable statical disadvantages. Those were partially compensated by the invention of concrete fillings in spandrels. The fillings increased arches' stiffness. The arches were placed on massive supports, providing necessary resistance to lateral forces.

In aqueducts, exemplifying one of the greatest engineering work in history of mankind, however, the stone construction of repeated arch pattern was statically stable. In adjacent arches horizontal components of forces have opposite directions and their sum equals zero.

In Ancient Rome the arch became also a very important decorative and monumental element (Fig. 2-7).

The bridge over the Gard river in Southern France (Fig. 2-8) represents one of the best preserved Roman aqueducts.

Among the numerous buildings of Mesopotamia, the Tak-i Kesra palace should be mentioned. This palace, built in the middle of the IIIrd century A.D. by king Shapoor, contained a magnificent royal hall. The pointed arch shaping the hall, still considered the biggest brick arch all the world over, measures 27 m in width and 37 m in height (Fig. 2-9). The palace suffered considerable damage caused by the 1909 flood, when the northern wall collapsed.

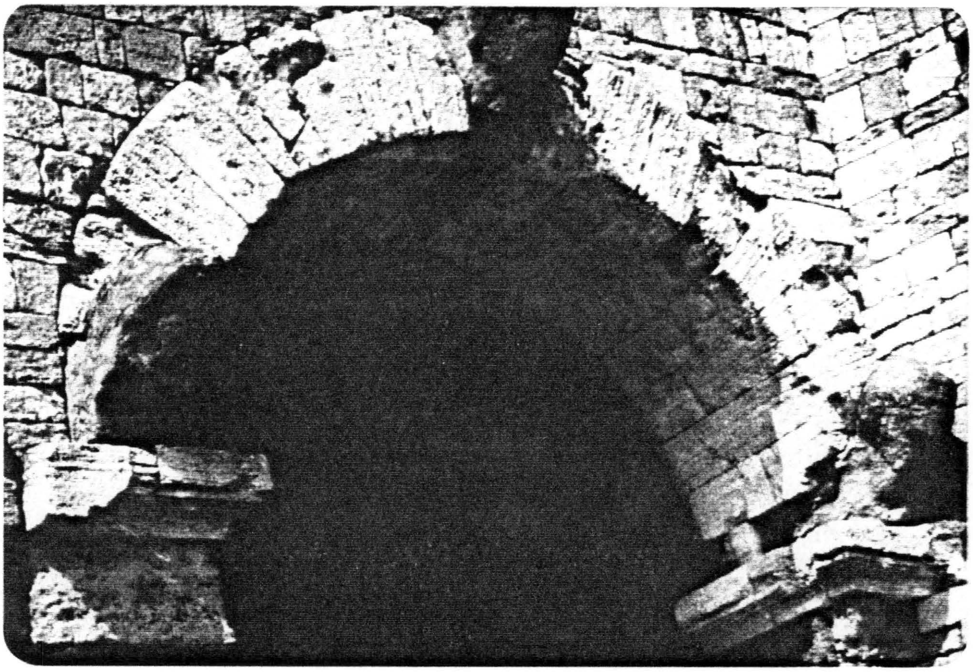


Fig.2-6. Arched Gate at Volterra; II cent. B.C.; considered the earliest example of the true arch in Italy.

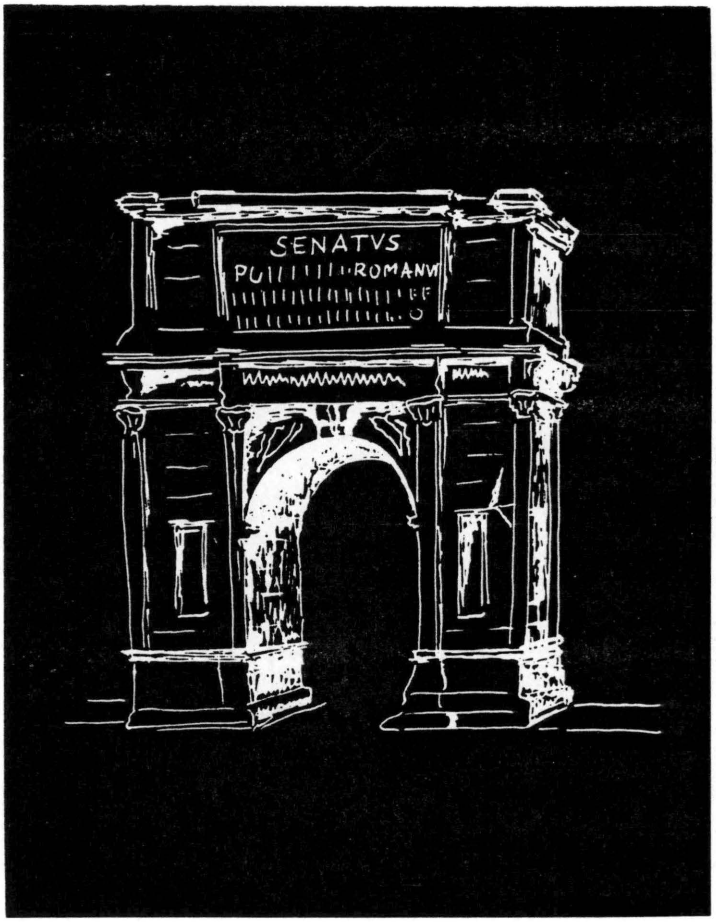


Fig.2-7. Rome: Triumphal Arch of Titus, 82 A.D.

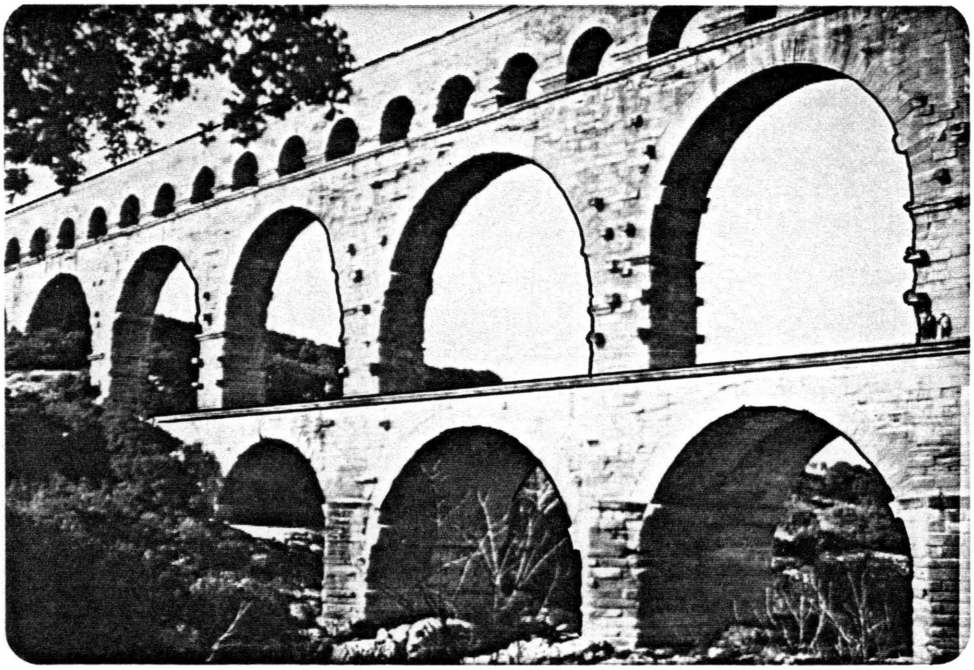


Fig.2-8. Roman aqueduct in Southern France.

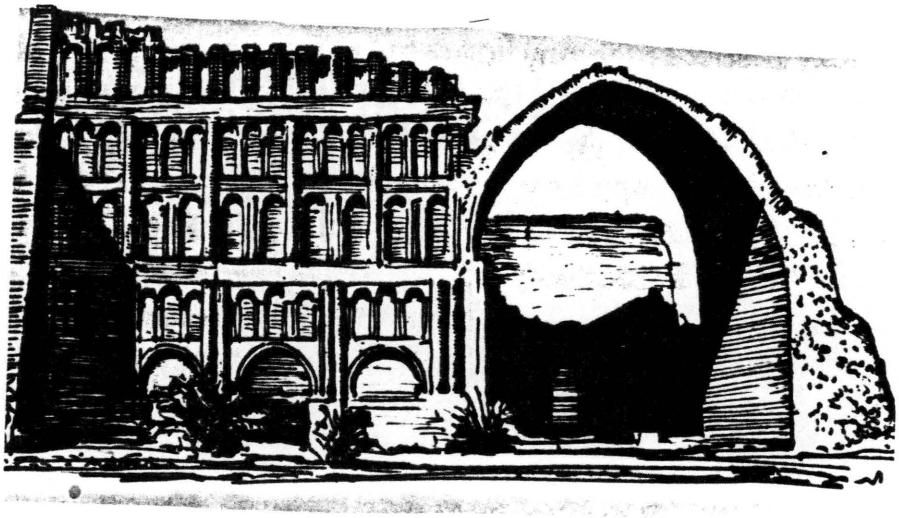


Fig.2-9. Ruins of the Tak-i Kesra Palace.

2.2. BYZANTIUM.

After the decline of Rome, during the centuries of stagnation in Europe, magnificent buildings were erected in Byzantium and in the train of the Arab conquests.

The Byzantine construction was performed according to the Roman practice. But even if the form of arches and vaults remained semicircular, the progress in technology was marked with new materials and solutions employed. The builders, concerned about earthquakes, appied iron ties stretching across the arches. Among the most magnificent buildings, Hagia Sophia of Constantinople survived till today in excellent shape. The brick dome has a diameter of over 33 m and is carried by four giant pendentives supported by semidomes 16.5 m of diameter each. Hagia Sophia was built in an incredibly short time (532-537), and remained the biggest arch construction for ten centuries.

The church of San Vitale of Ravenna, built in the middle of the VI c possesses a large dome constructed with earthenware pots to reduce its weight. The mausoleum of Theodoric in Ravenna has a flat, saucer shape dome consisting of a 35-ton limestone megalith. The lower arches have the indented voussoirs (Fig. 2-10), most probably serving as a safety measure against earthquakes. Finally San Marco of Venice must be mentioned as a masterpiece of Byzantine architecture. Begun in 828 and destroyed by fire its construction, in present shape, was designed in 1063. Its arches and domes provide not only the most logical and strong engineering accomplishment of the highest order, they also

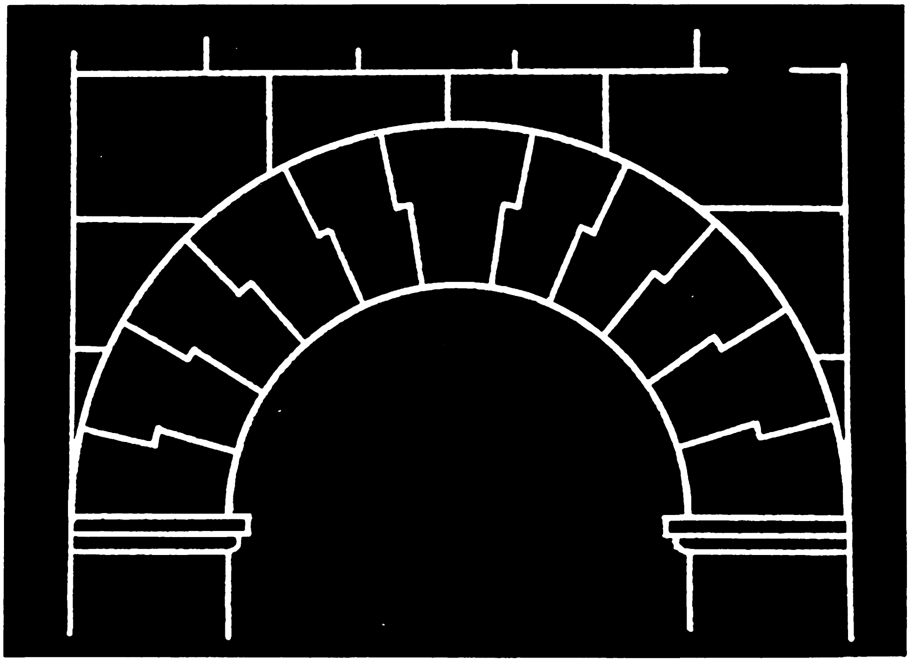


Fig.2-10. Indented voussoirs in lower arches of the Mausoleum of Theodoric in Ravenna.

create, like those of Hagia Sophia, the top achievements of the world architecture, the genius of human thought expressed in stone.

2.3. ROMANESQUE ARCHITECTURE.

When compared with Byzantine architecture, the Romanesque architecture of Western and central Europe seems primitive, heavy and monotonous. Developed in Lombardy, it spread with the help of master masons, mostly the brothers of the Cistersian and Benedictine orders. Romanesque sacred buildings possessed small doors and windows (Fig. 2-11), all of them round-arched, and barrel vaults of stone supported on thick heavy walls built of small-scale ashlar or brick. The application of arches continuously improved due to the experimentation with vaulting that went on.

Many of the early Romanesque vaults were of the barrel form. They were in turn succeeded by groined vaults with their weights and thrusts concentrated at the piers. The vaults were divided into narrow sections and the ribs carried the vault paneling. Except for large cathedrals in Italy, Spain, France, England and Germany most of the ecclesiastical buildings in Europe of this time were built rather modest, heavy and small.

Problems of Romanesque vaults are discussed in the next chapter; (Compare Fig. 2-14).

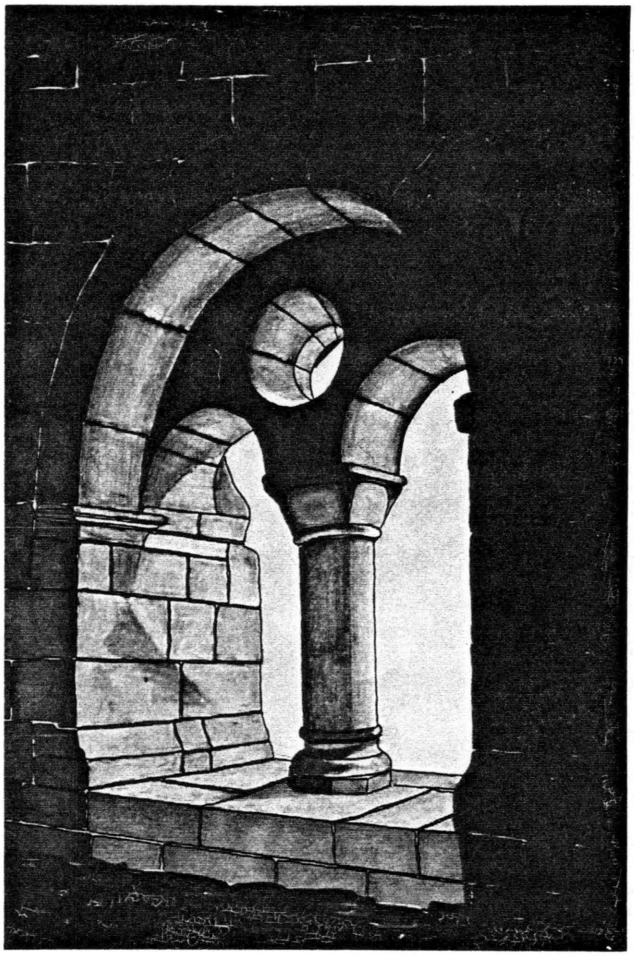


Fig.2-11. Cloister detail; Le Toronet, France.

Second half of the XII century.

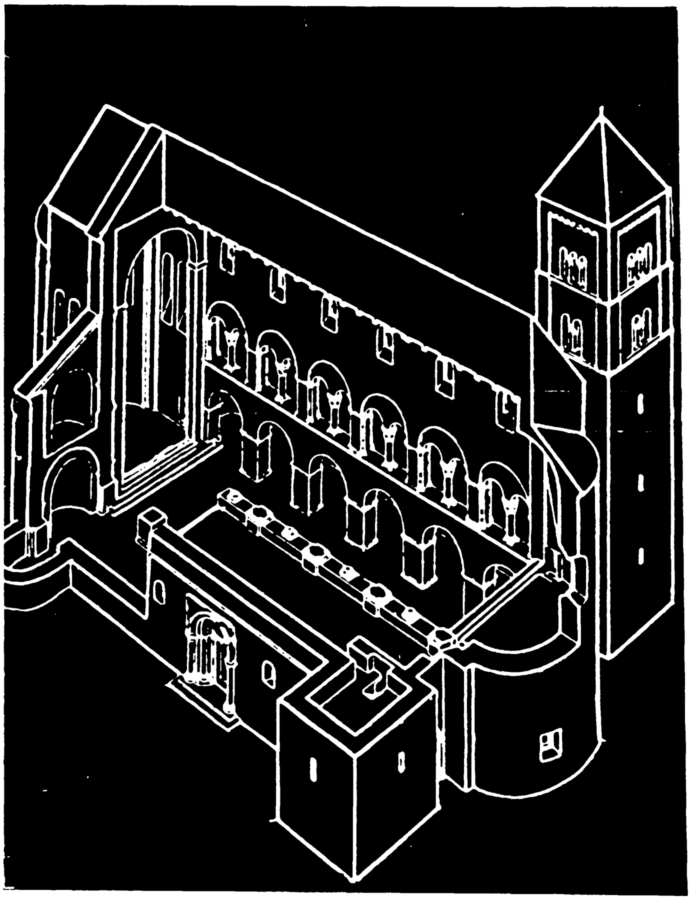


Fig.2-12. Reconstruction of the Romanesque church; Tum, central Poland, 1141-1161.

2.4. GOTHIC.

The development of Gothic, according to historians, was inspired by the growing power of the church and relevant intellectual awakening after centuries of stagnation; and breaking the isolation, achieved by the crusades. Hundreds of thousands of Europeans, mostly young, energetic and capable, were brought into contact with a superior technical civilization. The participants of the crusades got acquainted with the achievements of Arabic, Persian, and Jewish culture and science. Through Arabic schools the forgotten achievements of the Greek and Roman cultures were regained. Scientists of Toledo and Cremona translated the works of Archimedes, Ptotemy and others into Latin. The features of buildings found in Syria (and going as far back as Sumerian times) were repeated in the crusaders' fortresses and palaces along the Palestinian coast. These are the first buildings erected by European builders with pointed arches, and are considered the first examples of the newly born Gothic style. But even if the arches had typical features of Seljuk arches, as those in XI century Tomb Towers of Kharaqan (Fig. 2-13), they were very much simplified and devoid of sophisticated eastern ornamentation.

The first Gothic ecclesiastical buildings in Europe bore the features of the traditional Romanesque style. The windows and doorways retained rounded arches - even if, as in St. Denis of Paris (1144), considered the first Gothic church, all the vaults were pointed.The interior of St. Denis reminds one of the magnificent construction of Chartre Cathedral (1145) or Notre Dame de Paris (1163). The spires, towering towards the

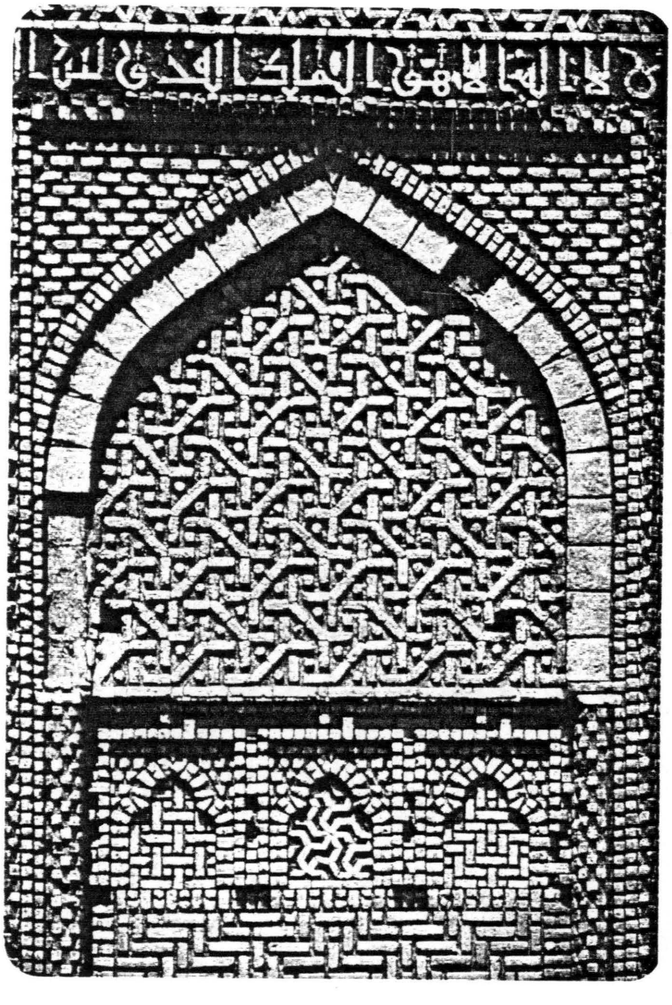


Fig.2-13. Detail of the Seljuk Tomb Tower.

skies, reflected the idea of human separation from the material problems of the life on earth.

In the Christian faith, in the Middle Ages, the pointed arched construction became a symbol of resurection of the soul, a religious symbol, in the way an arch has been for centuries a symbol of the Mohammedan faith.

The introduction of the pointed arch brought tremendous progress in building and enabled the solving of many difficult problems.

Formerly the builders had worked entirely with semicircular arches. Semicircular arches over a square did not give a simple solution, since the diagonal ribs, owing to the larger span, extended much higher than the transverse ribs across the nave. The builders had to manipulate the arches to obtain the same crown height. If the transverse arches were kept semicircular, the diagonal arches had to be made eliptical (Fig. 2-14).

With pointed arches, levelling of the crowns of the arches became no problem, no matter what span had to be covered. All could be carried to the same height. The need to distort any arches no longer existed (Fig. 2-15).

The pointed arches brought two important features to the Gothic buildings. The heavy bearing walls could be substituted by piers (between which large windows could be designed) and a special system of buttresses was applied to absorb the vaults' thrust. The height of the building became a function of span of the arches employed. The smaller buildings were designed "ad triangulum" (Fig. 2-16) and higher ones as "opus ad quadratum" (on the square).

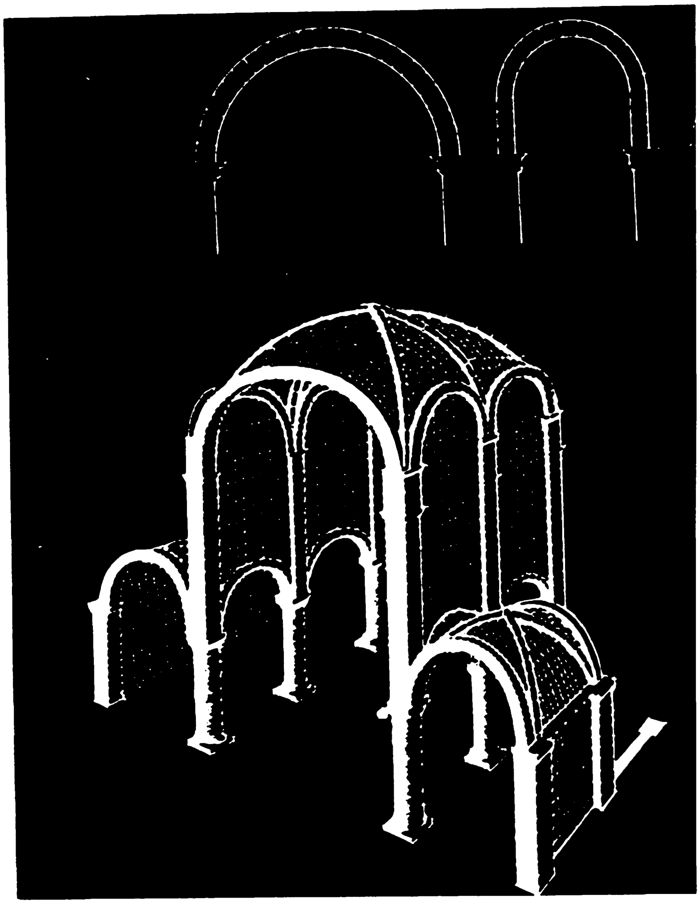


Fig.2-14. Romanesque ribbed vaults.

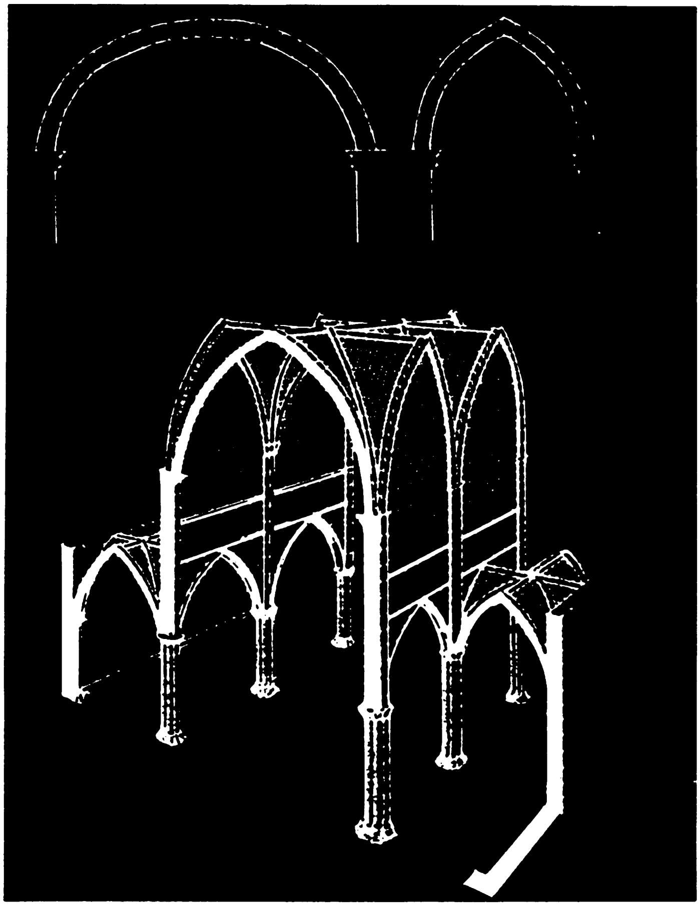


Fig.2-15. Gothic ribbed vault.

The buildings "ad quadratum" gave the possibility of dividing the square into four or six equal parts. The relation 1:2 between the width of the nave and its height (Fig. 2-17) could be changed to 1:3 (Fig. 2-18). There were also intermediate solutions (Fig. 2-19) between those mentioned, for instance in the cases when the church or other buildings had to be erected on the limited area available.

The application of bearing ribs made it possible to reduce the thickness of vaults as much as to 15 cm. The formulas and geometrical rules of construction were inherited by sons from their fathers. The rib vaults, the buttresses, the system of foundation, were based mostly on the experience and intuition. The details served three purposes: functional, structural, and aesthetic. All those became one.

The survival of those magnificent buildings proves their technological perfection. The recent researches of the Gothic cathedrals give scientific explanation to detailed solutions. This problem is discussed in chapter 1.2.

Even if the Romanesque buildings did not differ to much extent in particular European countries, we can clearly speak about French Gothic, Spanish, English, German "Hoch und Sonder Gothic", Polish Gothic, etc. as the builders in those countries developed some special forms obeying at the same time the basic, universal rules. Vernacular Gothic features were influenced by environmental, traditional and climatic factors.

Notre Dame de Paris, erected on comparatively strong soil, did not provide the builders with foundation problems, which certainly was not a case with, famous for its vast marvellous stain glass windows,

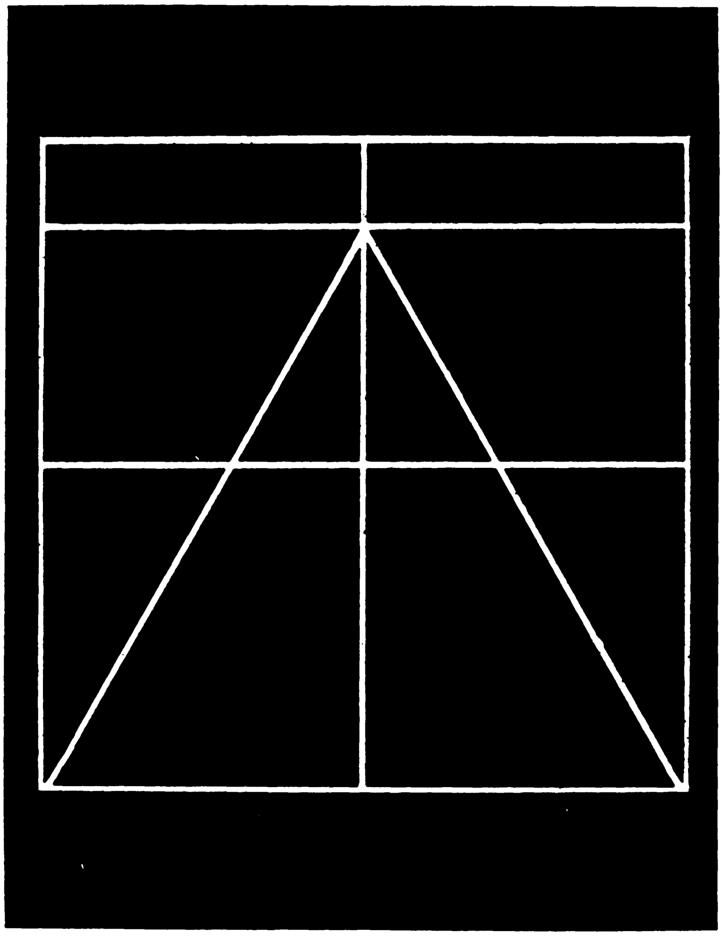


Fig.2-16. Gothic: "opus ad triangulum".

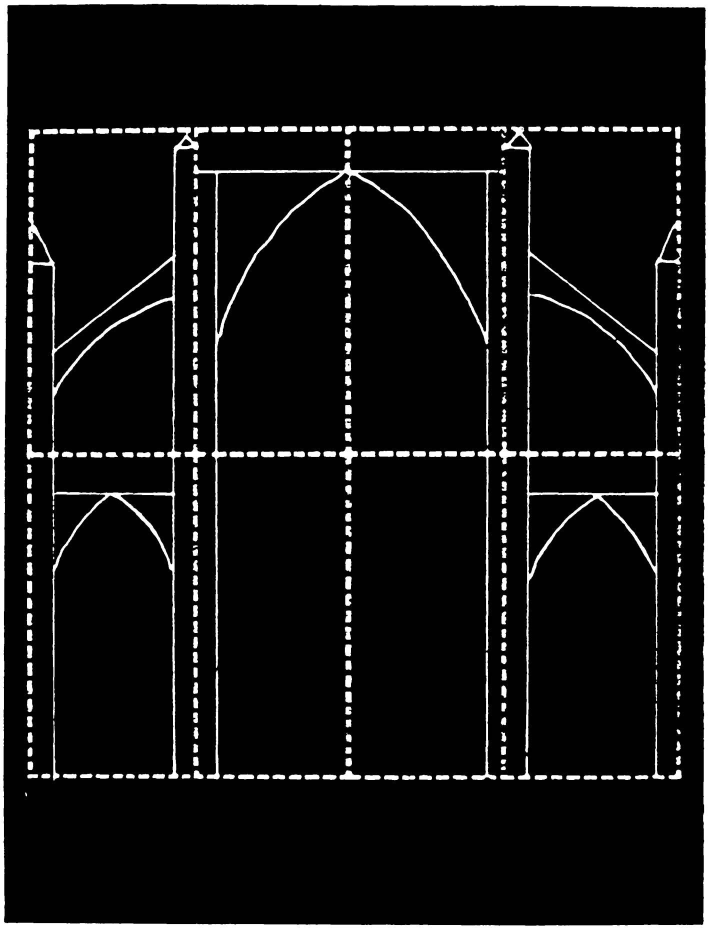


Fig.2-17. Gothic: "opus ad quadratum" 1:2.

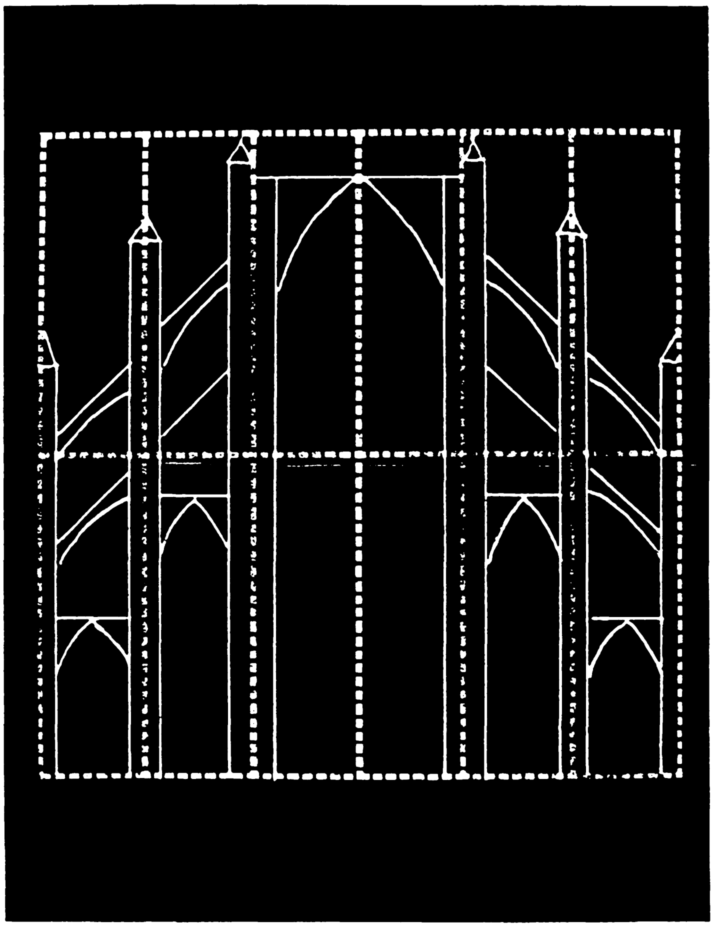


Fig.2-18. Gothic: "opus ad quadratum" 1:3.

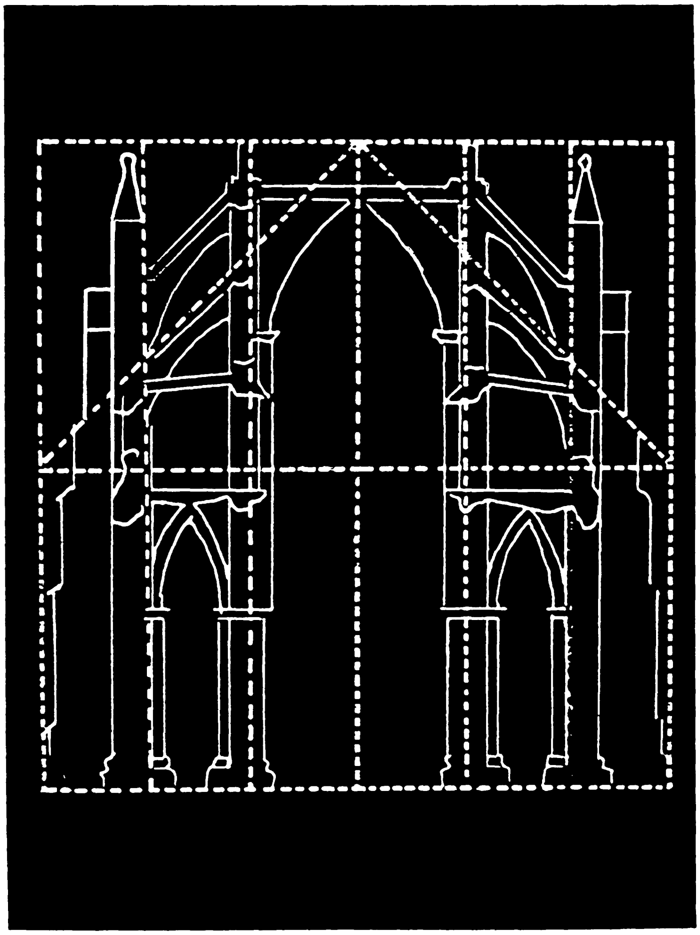


Fig.2-19. Gothic: proportions of Westminster Abbey.

St. John Cathedral of Gouda (in the Netherlands) where extremely light wooden vaults had to be applied. Due to the prevailing cloudy skies on most of the Dutch North Sea shore Gothic buildings were equipped with large windows to provide proper natural illumination.

The flying buttresses such as applied in the French cathedrals of Paris (Fig. 2-20), Reims, Chartres or Amiens would have been quite impractical in climatic conditions of severe Polish winters. Due to the extreme expansion in summer, and contraction in winter, melting snow and rain water may enter the joints between masonry units, freeze and cause spalling of the stone or brick. That is why only two churches, out of hundreds of Gothic churches in Poland, possess flying buttresses. Moreover, considerable number of churches, with the most magnificent example of St. Mary of Gdańsk, have the buttresses hidden inside, leaving the exterior walls plain. The Polish Gothic (the so-called Vistula Gothic) is characterized also with rather soft lines of the pointed arches, i.e. with comparatively small f:L (Fig. 2-21).

Another characteristic feature of the Polish Gothic is the system of Piast vaults introduced at the very beginning of Gothic building in Poland. Piast vaults were erected with nine-division system over the nave as well as over typical aisles. The piers look like pieces cut from a wall and the vaults match nave bays to narrow window units.

The Czech gothic masters favored the main nave divided into two parts with a longitudinal row of columns which gives an extremely interesting interior design. One of the finest examples of such design is the collegiate church at Wiślica in central Poland, in its present shape, completed in 1346 (Figs. 2-23 and 2-24). The nave is vaulted like the

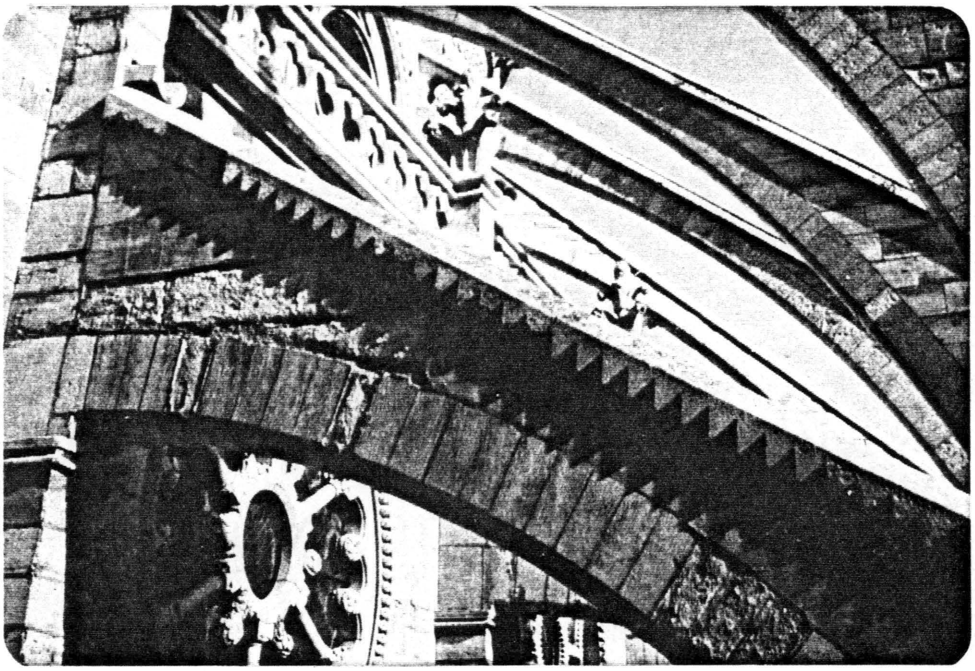


Fig.2-20. The flying buttresses of Notre Dame de Paris.

Fig.2-21. Cracow: Franciscans' Church, XIII-XV cc.

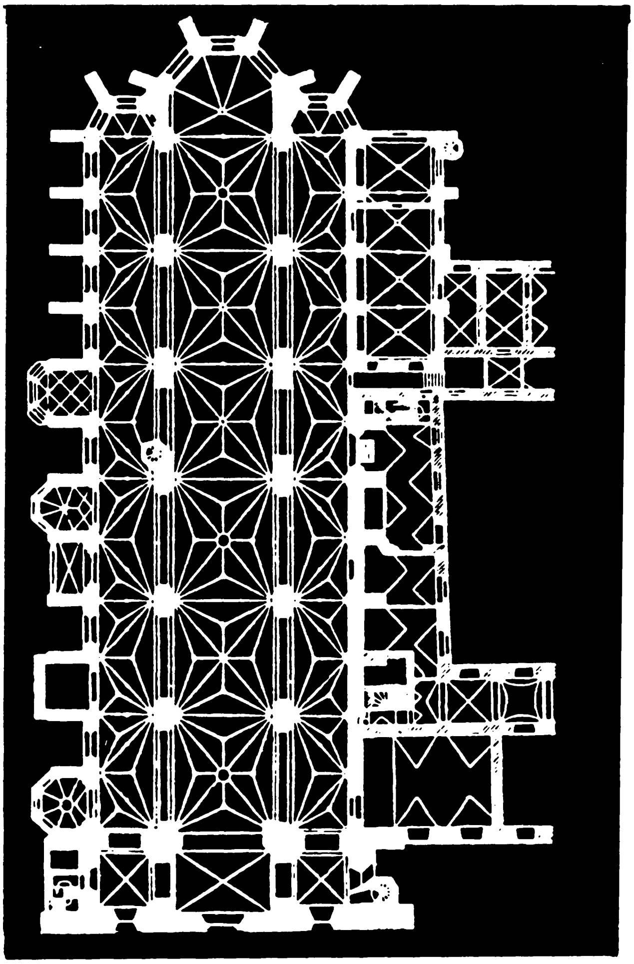
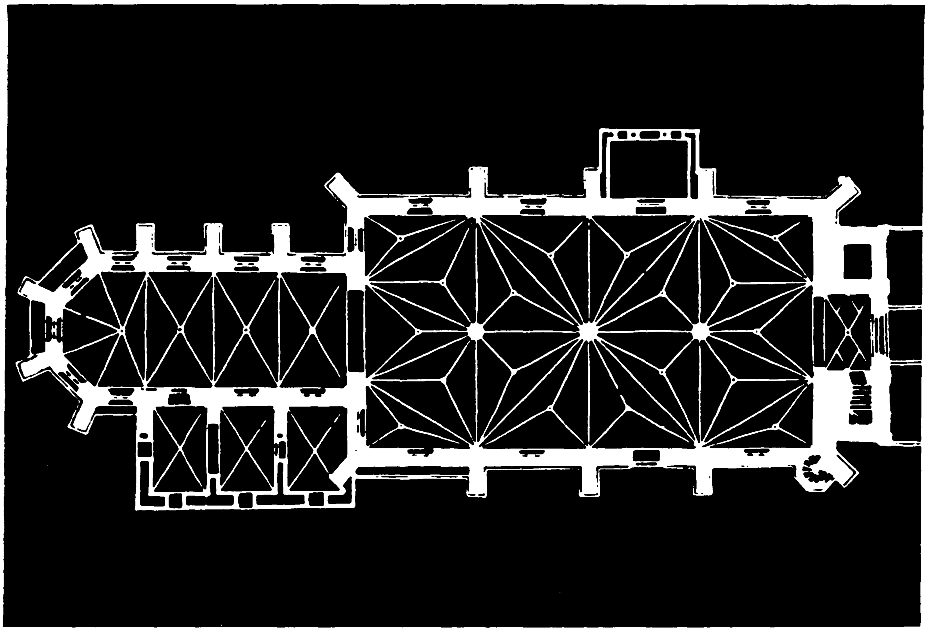


Fig.2-22. Wrocław: St. Mary On the Sand (1334-1369); over typical aisles Piast vaults.



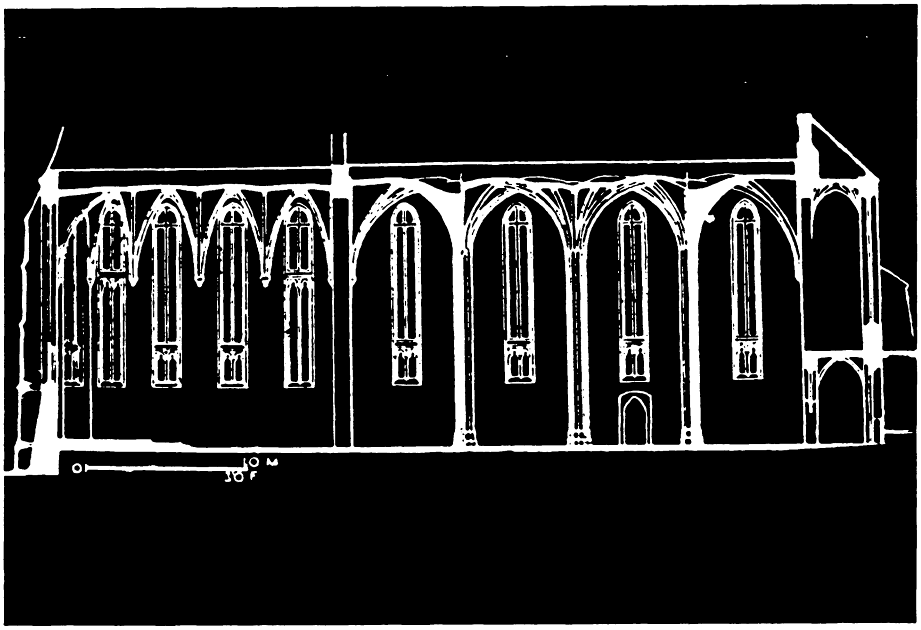


Fig.2-23. Wiślica, Poland: Collegiate church - plan.

Fig.2-24. Wiślica - cross section of the Collegiate.

refectory of some huge monastery. The system of ribs start from three central pillars with many branches, and absorb spreading force with ingenious corner spaces. This is one of the churches I like the best. Its construction is sharp and clear. Rib profiles, ingenious bosses, pillars with as many sides as ribs grow from them.

Speaking about evolution of Gothic vaulting, the fan vaults should be mentioned with an outstanding example of the Henry VII Chapel in Westminster Abbey.

It is interesting to trace developments of Gothic style in particular countries and technical improvements successfully applied. In England, for instance, where most churches were covered with timber roofs, the builders developed new solutions that have never since been excelled.

As it is well known, in ordinary pitched roofs ties or collar beams are needed to prevent rafters from spreading outwards and insure necessary stiffness of the construction exposed to wind forces. Such beams would have obstructed the light when hanging low in front of magnificent church windows. The hammer beam truss, developed in England, is a tie beam from which the middle part of the beam and a central post have been removed. The ridge timber (a purlin) is supported by a vertical leg resting on a hammer beam. The thrust exerted on the hammer beam is partly transmitted directly to the wall and partly to the lower section of the wall with the help of a lower arch (Fig. 2-25).

The masterpiece of the construction should not be underappreciated when we take into consideration the tremendous weight of the roof, which, as it was usual also in French cathedrals, was covered

Fig.2-25. London: A roof of Westminster Hall.

On the right hand a hammer beam

- a masterpiece of Gothic timber structure.

with lead. The weight of the lead tiles alone, without rafters, battens etc., exceeds 65 kg/sq m. It seems interesting to note that tiles were fixed to battens with large headed iron nails.

Masters of Late Gothic, obeying the strict rules of construction, introduced more elements of color and ornamentation, to give the example of the cathedral of Sandomierz, and the royal tomb of Kazimierz the Jagiellon, sculptured by Wit Stwosz in 1492 (Fig. 2-26).

In the last phase of Late Gothic, rib-vaulting often lost its constructional function, and became a decorative form. The famous Vladislav Hall in the Hradčany Castle, Prague, exemplifies such a "degeneration of the pure style" (Fig. 2-27).

Many Gothic churches in England, and especially in Spain (influenced by Arabic architecture) can hardly be compared with the very first Gothic buildings representing severe simplicity and clear, logical construction. One of those, I had a chance to admire, has been St. John's of Toledo, with the adjacent magnificent monastery.

While the Gothic style was spreading all over Europe the Islamic countries were developing new sophisticated vault and dome structures. The structures abounded in variety of forms and shapes. The cross section of Yeşil Mosque (Green Mosque) of Iznik, Turkey (Fig. 2-28) exemplifies three kinds of domes with different natural illumination and supporting systems. The walls, growing thicker below the domes, form stiffening rings.

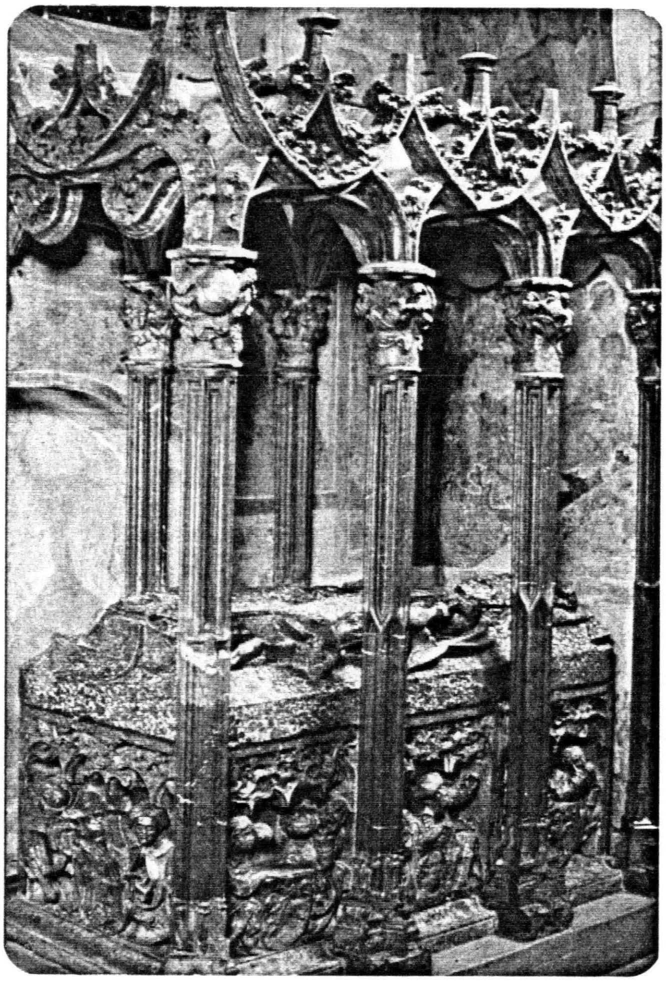


Fig.2-26. Late Gothic tomb in Cracow Cathedral.

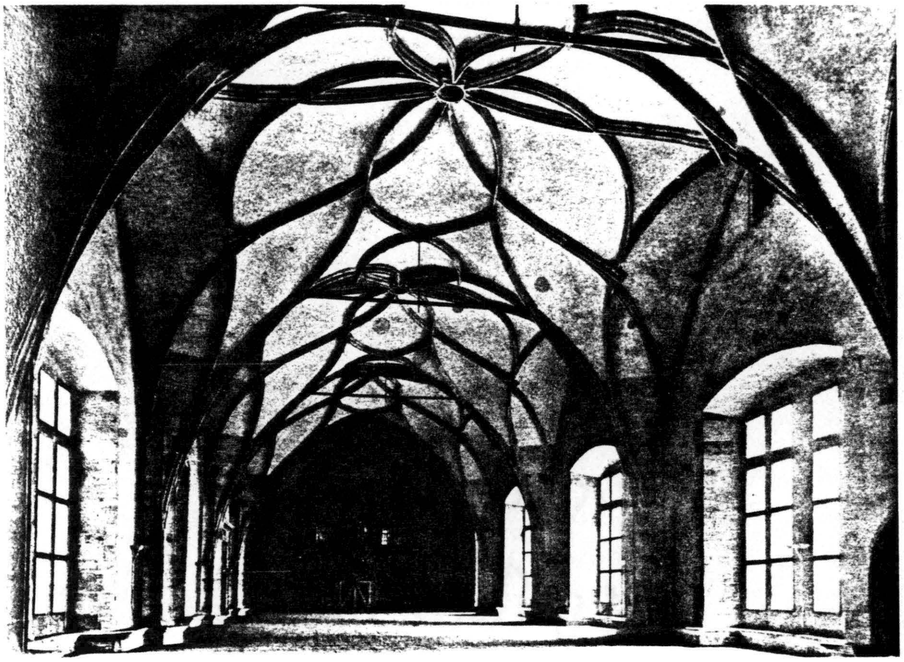


Fig.2-27. Prague: Vladislav Hall of Hradčany, 1484-1502.

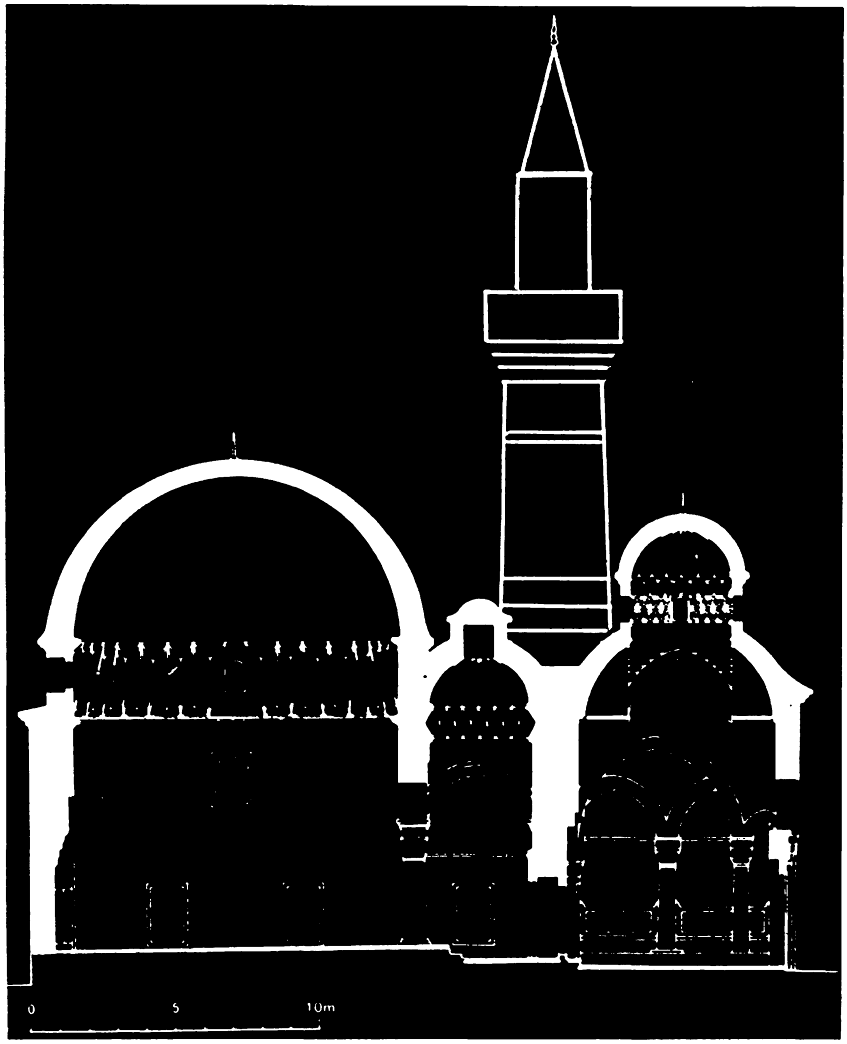


Fig.2-28. Iznik, Turkey: Yeşil Mosque, 1378-1391.

2.5. THE RENAISSANCE.

After the centuries of gothic building, the idea of rebirth in architecture was conceived in Italy. The Italians looked back with nostalgia to the times of Rome, its power, and cultural achievements. The dream came true, when Federico Montefeltro with a help of the Florentine architect Filarete built a new palace in a style representing "good contemporary architecture". The theoretical background for the new style was made by Brunelleschi and Alberti.

The main beliefs which brought about the revival of classical architecture were that the Roman Empire was destroyed by the barbarians, and the products of mediaeval culture: art and architecture produced by those barbarians had to be barbaric itself. The aristocracy brought up in new ideas demanded from architects buildings which could represent the classical decoration and splendor of the past. Architects began to study ancient ruins to fulfil these demands.

In renaissance buildings arches and vaults served two purposes - structural and aesthetical. The equilibrium of structure and form was not observed in the way followed by the gothic masters. Arches became also a very important decorative element. Santa Maria del Fiore of Florence with its marvellous dome structure exemplifies this trend. Arches on the external walls of the church mark masterpiece ornaments (Fig. 2-29).

A new technology of erecting domes was invented. Complete rings of stones were laid up horizontally in a way the corbeled structures had been built in Mycenae. An elimination of framework enabled the erection

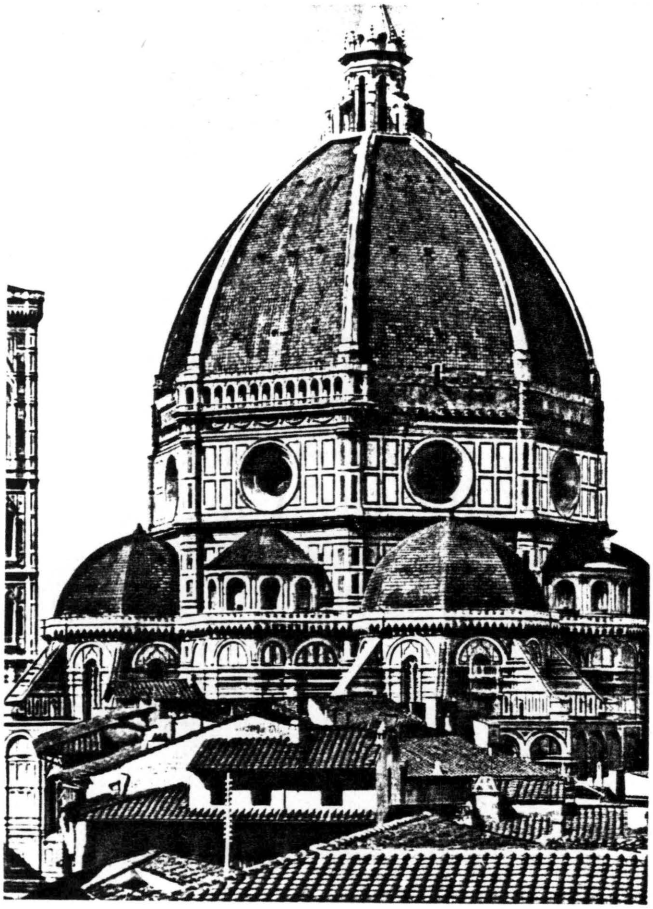


Fig.2-29. Florence: Cathedral cupola.

Built 1419-1436 by Brunelleschi

with its Gothic ribbing represents new Renaissance style.

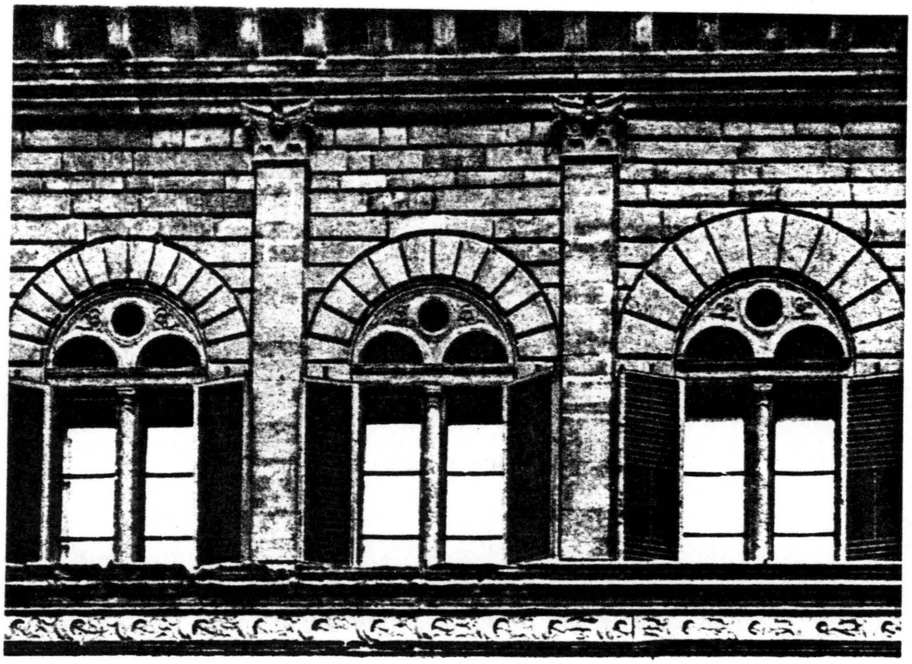


Fig.2-30. Florence: Detail of the Palazzo Ruccelai; designed by Alberti, 1446.

Fig.2-31. Vatican City: St. Peter's Basilica.

Begun by Bramante in 1506, completed by Michelangelo,

it remains the largest church dome up today.

of huge domes like those of Florence and Vatican.

The new style spread all over Europe - France, England, Spain, the Netherlands and Germany. One can also find many examples of Renaissance buildings in Poland. The Kingdom of Poland with its 1,000,000 sq kilometers represented one of the most powerful countries in XV and XVI century Europe. Cracow, the capital, was one of the biggest cities. King Sigismund the Old married Italian princess Buona Sforza, who promoted a lot of outstanding masters brought from Italy. Many of them settled in Poland for ever, and even changed their names to sound pure Polish.

The Wawel royal castle was enlarged and reconstructed in the new style (Fig. 2-32) by Francesco Fiorentino (1502-1516), Master Benedykt (1524-1529) and Bartolomeo Berrecci (1530-1536). Famous Sigismund Chapel was built by Berrecci in 1517-1533 (Fig. 2-33). The same artist made sculptural decorations.

When compared to Gothic building, the new style introduced incredibly sophisticated and subtle construction. The ornamentation of interiors was perfected by the lavish illumination with daylight entering through the broad windows and skylights. The arch became also a very important element of interior decoration (Fig. 2-34).

Renaissance builders used mostly semicircular arches according to their Roman predecessors. This was considered one of the basic rules of classical order. As for vaulting, pointed sharp vaults had been replaced with semicircular soft vaults. Parish church of Kazimierz on the Vistula in central Poland retained Renaissance style with local ornamentations (Figs. 2-35 and 2-36).

Fig.2-32. Cracow: Arcaded courtyard of the Wawel Royal Castle.

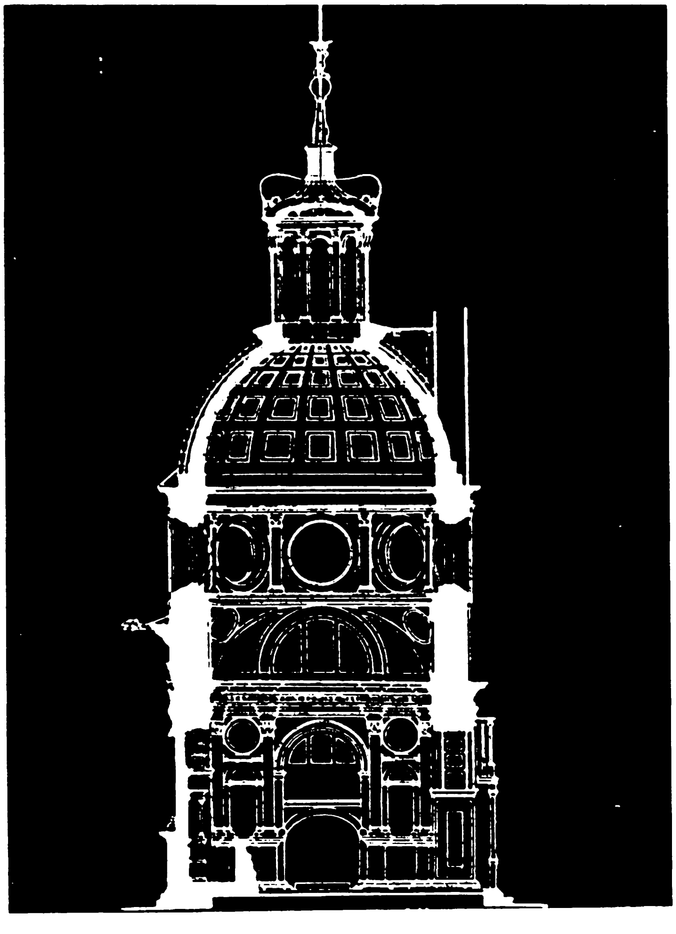
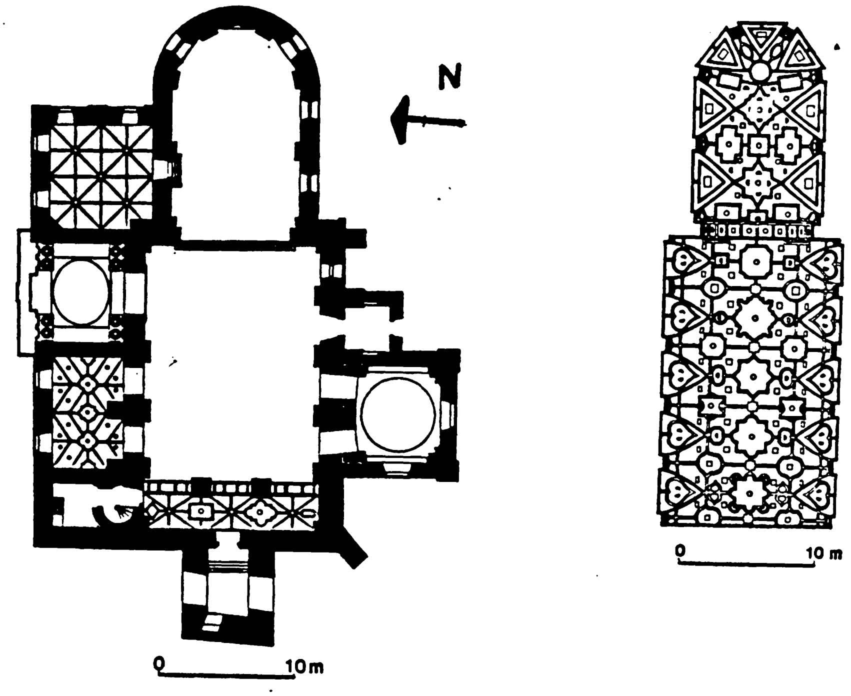


Fig.2-33. Cracow: The Wawel Cathedral; Sigismund Chapel.

Fig.2-34. Cracow, Wawel: The tomb of Sigismund August sculptured by Santi Gucci, 1571-1574.



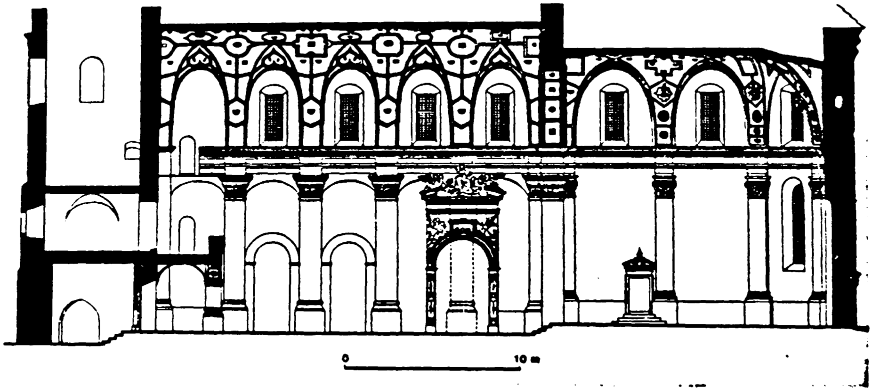


Fig.2-35. Kazimierz Dolny, Poland:

Plan and vaults of the parish church (1586-1589).

Late Renaissance/Mannerist decoration by Balin (1625-1629).

Fig.2-36. Cross section of the same church.

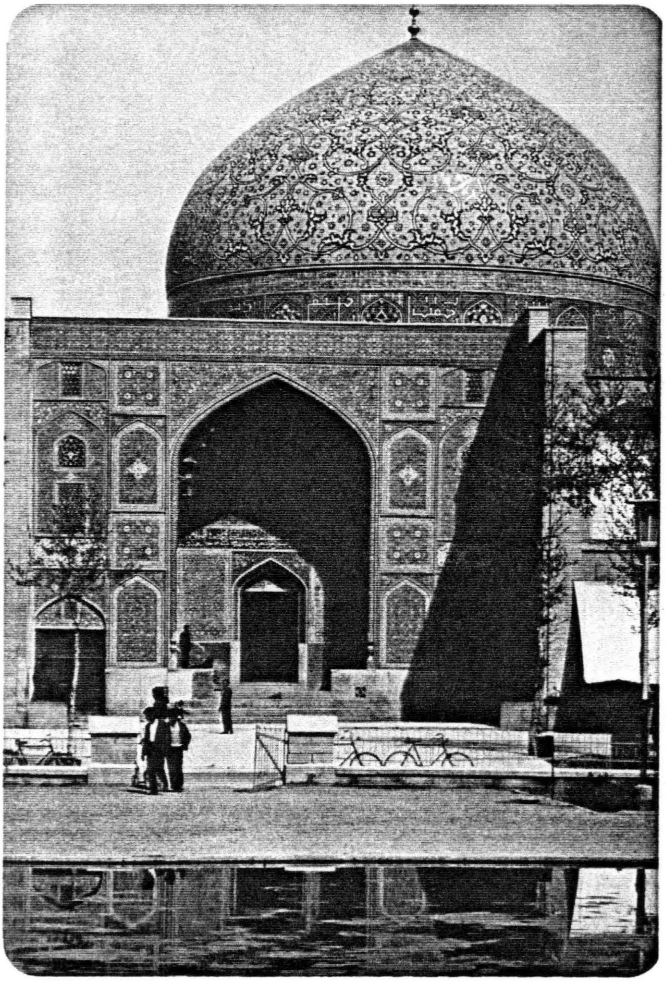


Fig.2-37. Isfahan: Masjid-i-Shaykh Lutfullah, 1601-1618.

The Islamic architecture has retained distinct features.

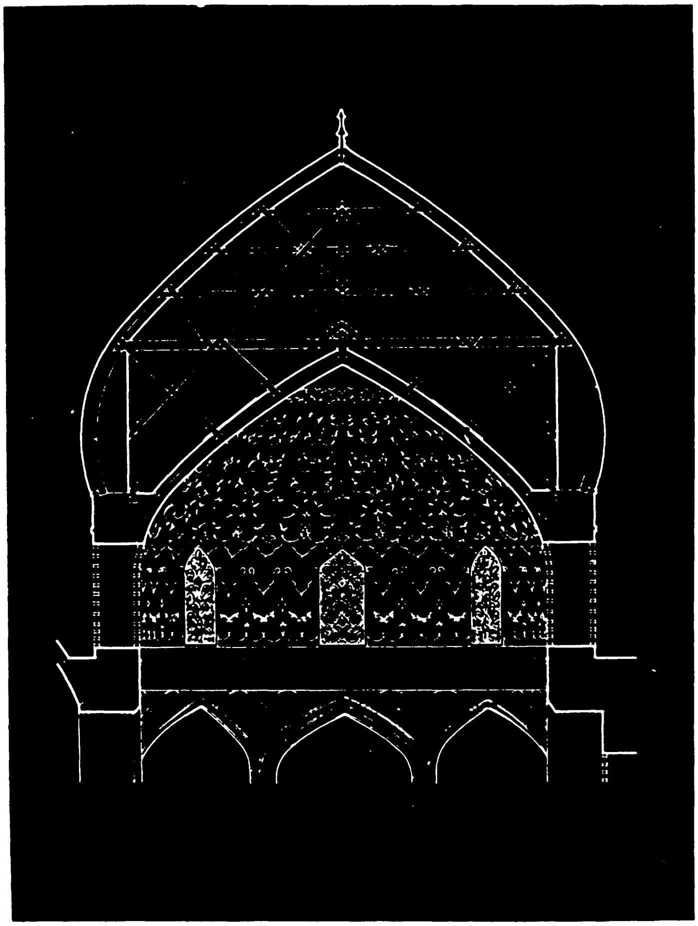


Fig.2-38. Isfahan: Great mosque of the Shah.

The outer shell is supported by a system of wooden props inside the blind space.

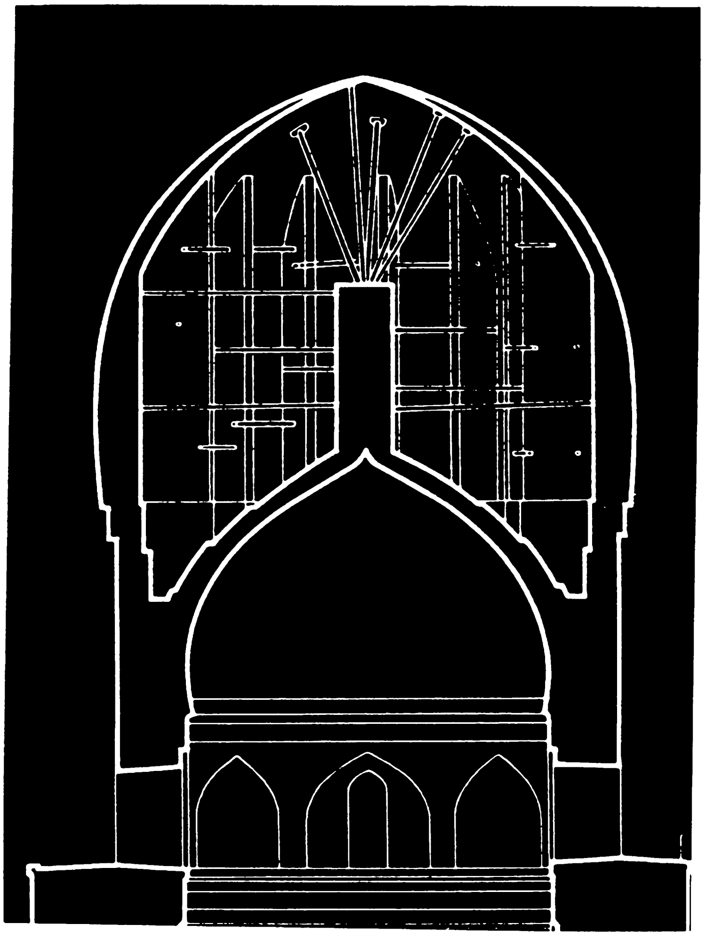


Fig.2-39. Samarkand, USSR: Tomb of Tamerlane. The outer shell is supported by timber props. They rest on the massive masonry column placed exactly in the center of the pointed dome.

2.6. BAROQUE.

Baroque constitutes the revolt against pedantry of the late Renaissance. The flat arrangement of elements, artistic expression in classical facades were to be replaced by a new conception of space. This meant a new approach to architecture, understood not only as creating single buildings, but new ideas of putting the buildings together and developing contemporary principles of town planning.

The conception of free space could develop with progress in technology, expressed in better materials and the improved control of their application. Architects tended towards monumental planning and arrangements. Straight lines were replaced by curved lines expressed in variety of arches.

All that could be materialized due to developments in building construction, and especially in wood structures. The new improved roof trusses made it possible to apply suspended or plastered vaults. In Baroque churches and buildings the vault and the roof often do not constitute two separate elements (Fig. 2-45).

Arches abound in Baroque architecture. In addition to semicircular, a wide variety of different shapes and forms have been used.

Works of Bernini and Borromini in Italy, Mansard in France, Inigo Jones and Sir Christopher Wren in England, Tylman Van Gameren in Poland and many others represented the highlights of the new style.

A great number of baroque churches, palaces and residences have been erected in Poland. The Cistercian Abbey at Krzeszów is considered as one of the most interesting examples (Figs. 2-40 and 2-41). The

Fig.2-40. Krzeszów, Poland: Cistercian Abbey; 1728-1735.

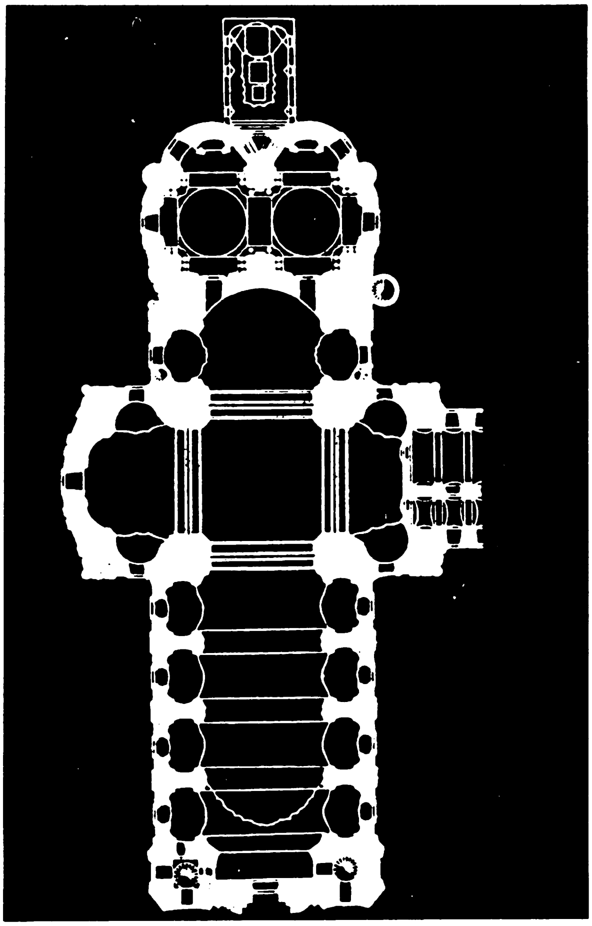


Fig.2-41. Krzeszów: Plan of the Baroque church; (shown in Fig.2-40).

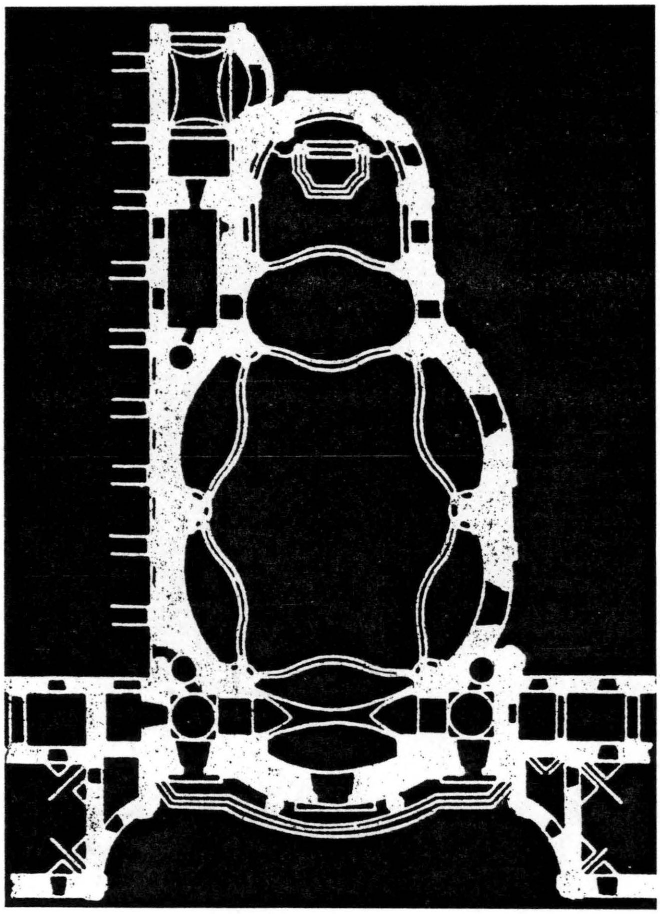


Fig.2-42. Legnickie Pole, Poland: Church of Saint Jadwiga.
Founded in 1241, reconstructed by Ignacy Dientzenhofer abt.1730.
Six great pillars bear individual chunks of entablature.
The oval dome becomes a kind of baldacchino
supported on six sophisticated arches.

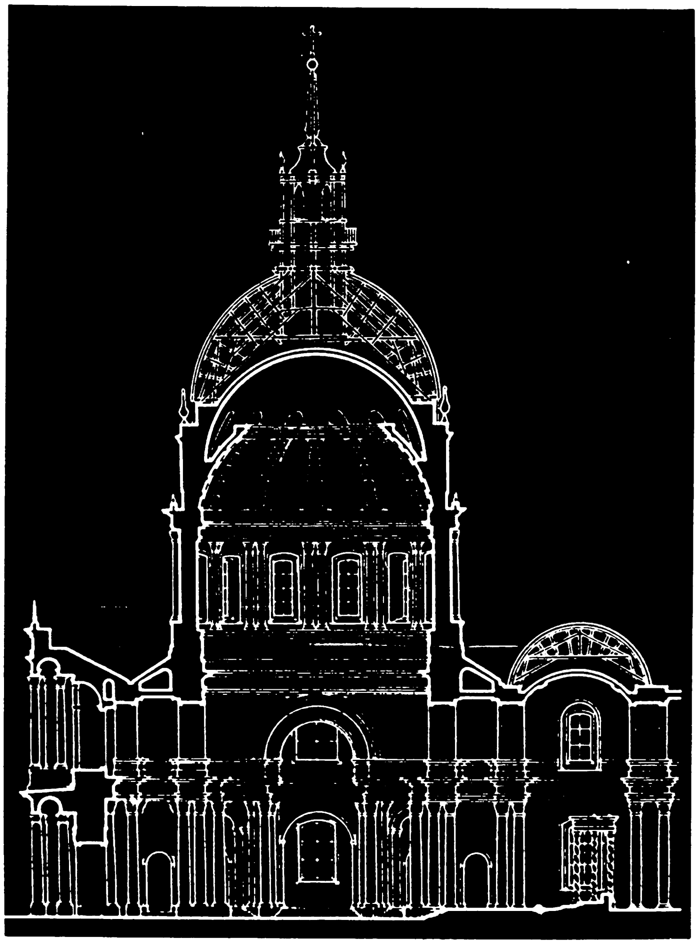


Fig.2-43. Paris: St. Louis des Invalides.
Designed by Jules Hardouin-Mansard in 1676,
exemplifies a sophisticated construction of the French Baroque.
The wooden space truss possesses the horizontal ties
over the masonry dome. The top ring of the incomplete dome served as
a support for a formwork for the erection of the upper dome.

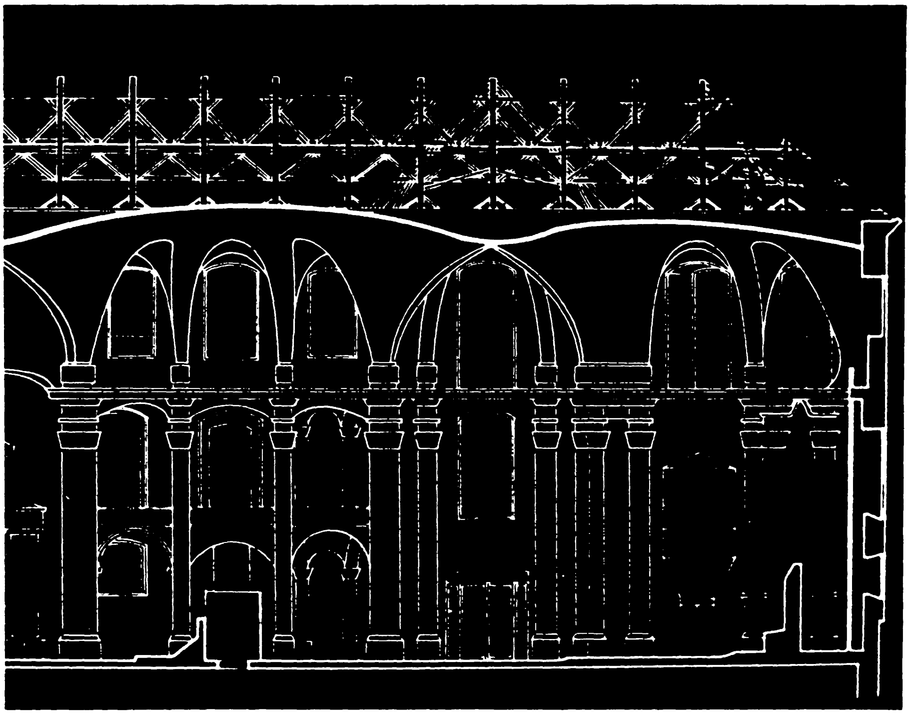


Fig.2-44. Vierzehnheiligen, Germany: Pilgrimage church. Built between 1743-1763 by Balthasar Neumann exemplifies an arched construction of the late Baroque.

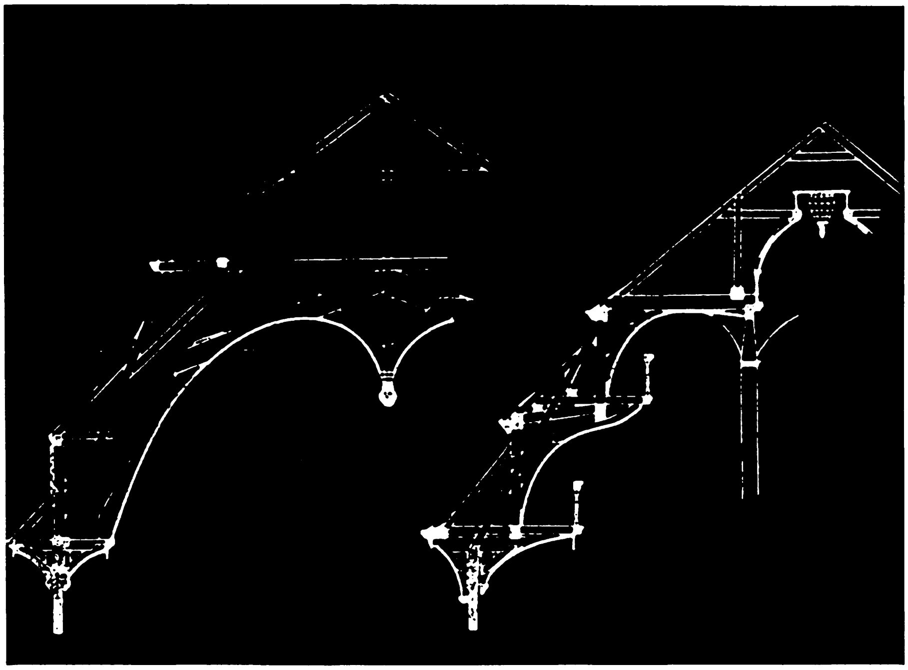


Fig.2-45. Northern Poland: Baroque roofs and vaults of synagogues, beginning of XVIII century.

sophisticated system of walls supports domes and two-way vaults spanning over the nave and aisles in two perpendicular directions.

In Rococo curves multiplied both in plan and in elevation. Ornaments often dominated over construction. Line of forces were not immediately clear for the spectator, especially what was marked in transition arch - support, and vault - wall. Frescos on vaults became common with new perspective introduced earlier in the time of Renaissance.

It is always difficult and controversial to write about pure style. Any style understood as a result of general tendencies in aesthetic trends and patterns is a resultant of individual taste, sensitivity, intellectual capability and professional skill of designers.

Speaking about general tendencies, we have always in mind variety of solutions, blending of different influences, seeking for originality even if the artists conform to basic demands of fashion and rules established at the given time.

Very often the Maecenas had a predominant influence on architecture. He had a variety of means to do so, to mention only, that he could hire those who would follow his line to such extent that he would become a creator of some particular style more than individual artists. Examples abound throughout centuries.

Stanisław August Poniatowski, the last king of Poland, is remembered not as a skilled politician but rather as a great Maecenas and lover of arts. Under his artistic patronage the architects retained certain remnants of baroque ornamentation which co-existed with the neo-classical elements and general lay-out of the buildings, expressed mostly in departure from the baroque principle of axial composition. The

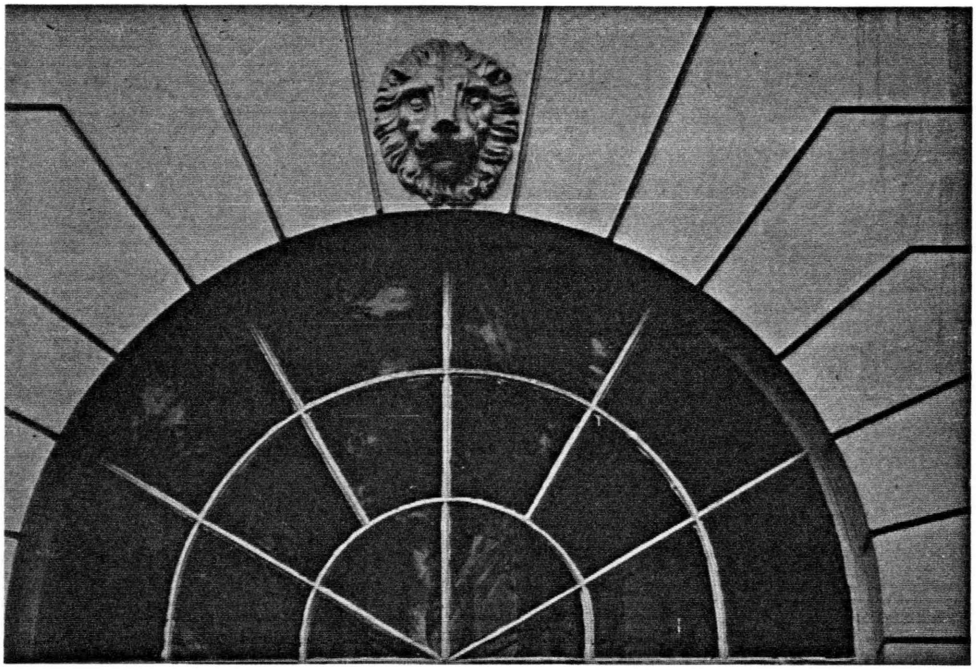


Fig.2-46. Wilanów, Warsaw: Arched lintel in the orangery.

palaces and residences in Stanislaus Style possessed extremely differentiated interiors with interesting vaults.

Like in the time of Baroque, in the Stanislaus Styled interiors of the Royal Castle of Warsaw & Łazienki Palace on the Water, vaults often do not serve structural purposes. Many of them are plastered. Large plafonds in central areas of the ceilings are placed over curvatures imitating lines of forces flowing into adjacent walls.

2.7. CLASSICAL REVIVAL.

Classical Revival constituted a reaction to the freedom of Baroque and Rococo. Again architects returned to classical order. The arches, to much extent, lost their most decorative function and again became elements of structural form.

The buildings of that period often successfully combined classical appearance with highly functional interiors. Behind the classical facade of the Great Theatre of Warsaw designed in 1825 by Corazzi was housed a spacious interior covered with long span arched construction. The theatre was completely destroyed during the Second World War and only the front wall survived. It has been rebuilt, steel trusses carrying vaults have been applied, and now meets the demands of the contemporary, modern theatre.

Another example of classical revival in Polish architecture, the Lutheran church in Warsaw, represents the pure classical approach of its designer S. Zug. Despite the common opinion that the dome is not desirable for good acoustics, this church is famous for its perfect acoustical performance.

Fig.2-47. Warsaw: Dome of the Lutheran Church, 1777-1779.

2.8. ARCHITECTURE OF TECHNOLOGICAL REVOLUTION.

The technological revolution of XIX century resulted in lower prices of iron and steel that permitted a wider use of these materials. The first arched cast iron bridge was built betweeen 1776-1779 by the owner of ironworks, Abraham Derby III, certainly for advertisement purposes. The bridge spanning the banks of the Severn at Coalbrookdale in Britain, has a span of 33 m and rise of 16.50 m (Fig. 2-48).

Since then rapid development in steel construction has taken place. As for arched constructions, they have been widely used both in bridges and public buildings. Later reinforced concrete and other materials entered the competition.

The XIX century, even if often considered as a decline in world architecture due to the chaotic developments of the new industrial areas, may be also seen as a transition to modern architecture of today. Progress in technology enabled the erection of numerous fascinating constructions of bridges and public buildings. Among those, arched constructions may be noted like the viaduct over Truyere at Garabit by Eiffel and a bridge over Vilaine at La Roche-Bernard, famous railway stations in Great Britain, or an exhibition hall in Paris (Fig. 2-45).

Numerous long span constructions, like the mentioned Paris exhibition hall, were performed as three-hinged arches. The three-hinged arches as determined statically have always been easier for design. Application of the new materials made it possible to apply improved and dependable construction of hinges.

Fig.2-49. Coalbrookdale, England: First iron bridge.

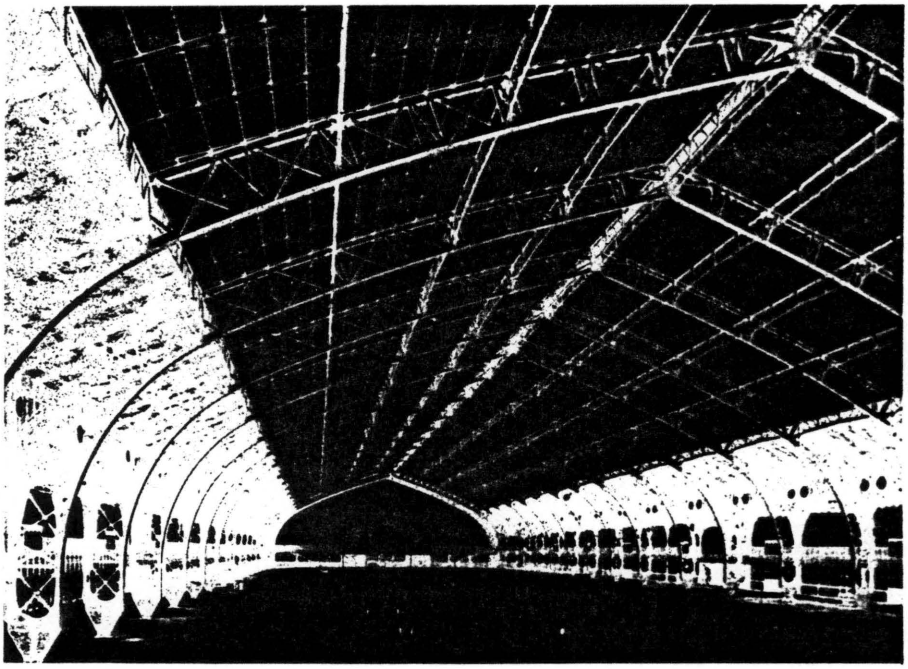


Fig.2-49. Paris: Machinery Hall at the International Exhibition.

Ferdinand Dutert and Contamin, 1889.

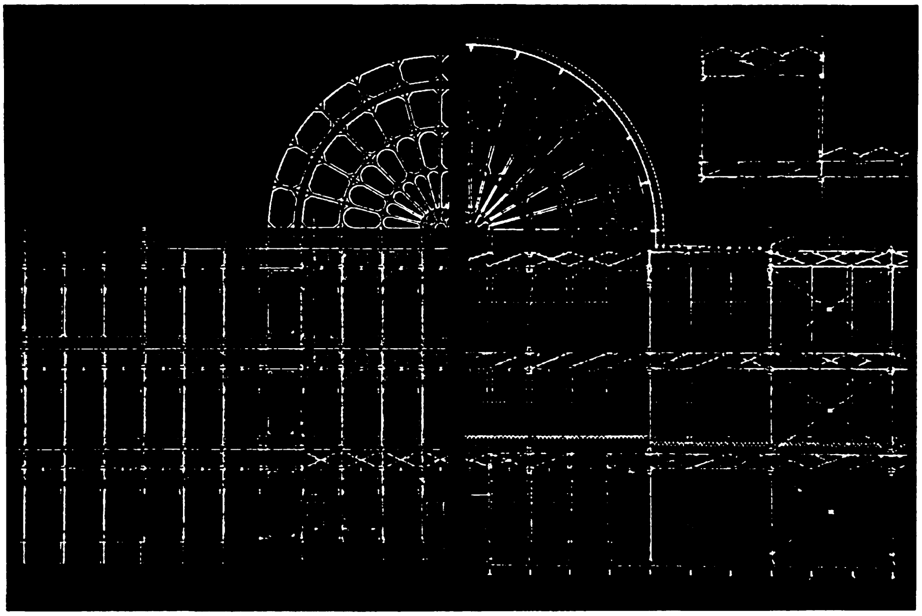


Fig.2-50. London: Crystal Palace. Joseph Paxton, 1851-1854.

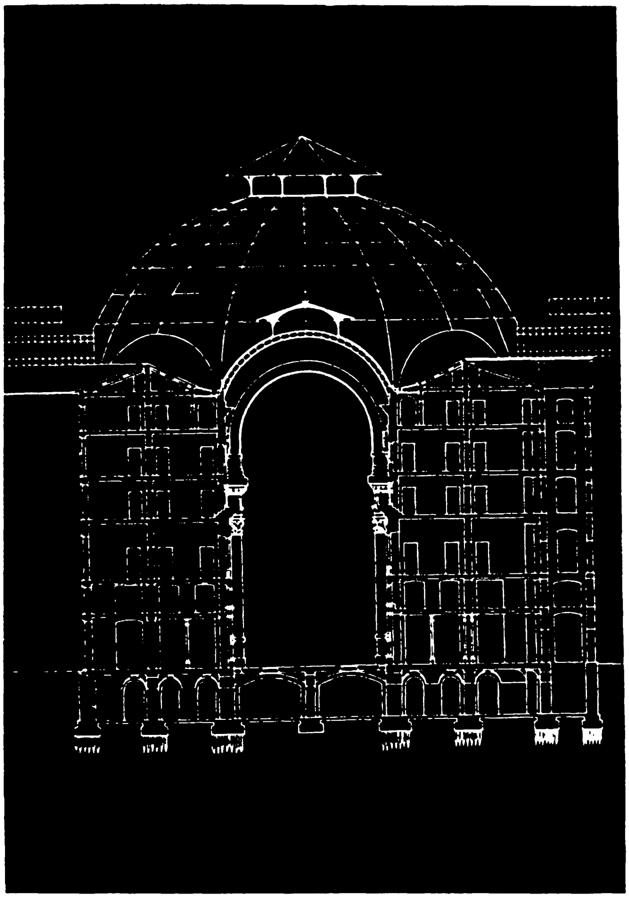


Fig.2-51. Milan, Italy: Galleria Victorio Emanuele II.

Giuseppe Mengoni, 1865-1867.

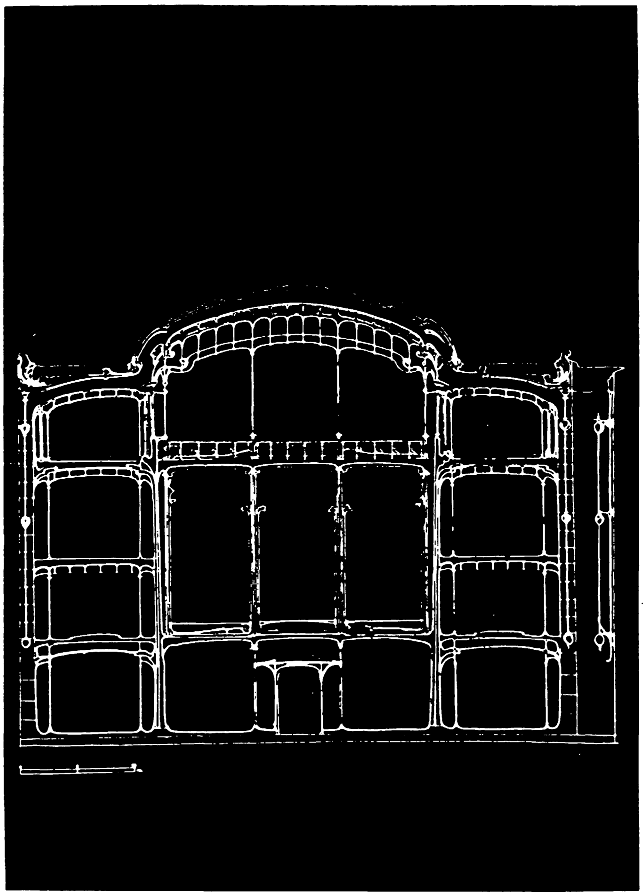


Fig.2-52. Brussels: L'Innovation - Department store. Victor Horta, 1901-1903. An interesting example of arched construction supported on cast-iron columns; the system applied in residential and industrial buildings at that time.

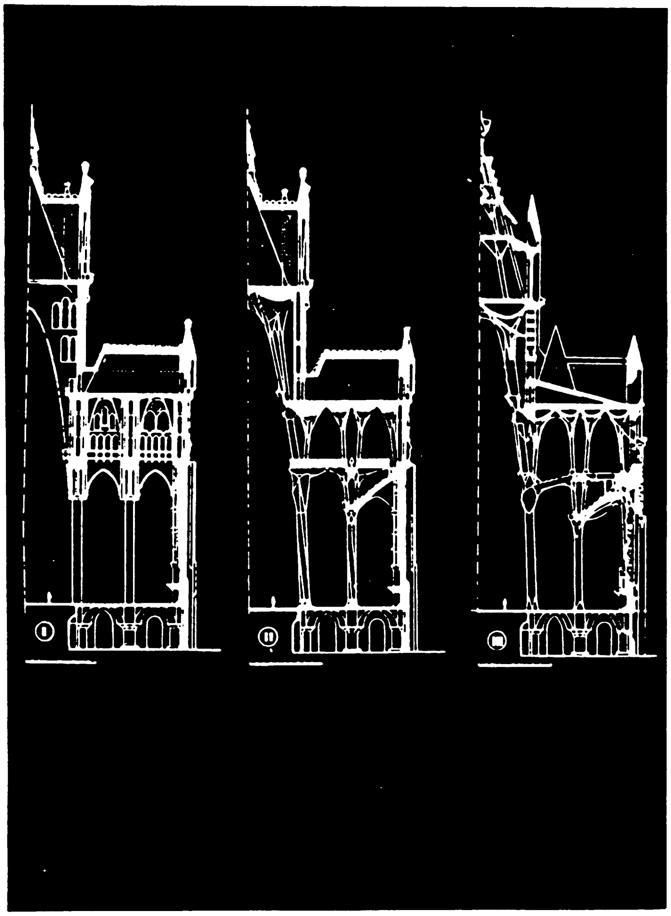


Fig.2-53. Barcelona, Spain: La Sagrada Familia.

Antonio Gaudi, 1886-1926. Three stages of the design.

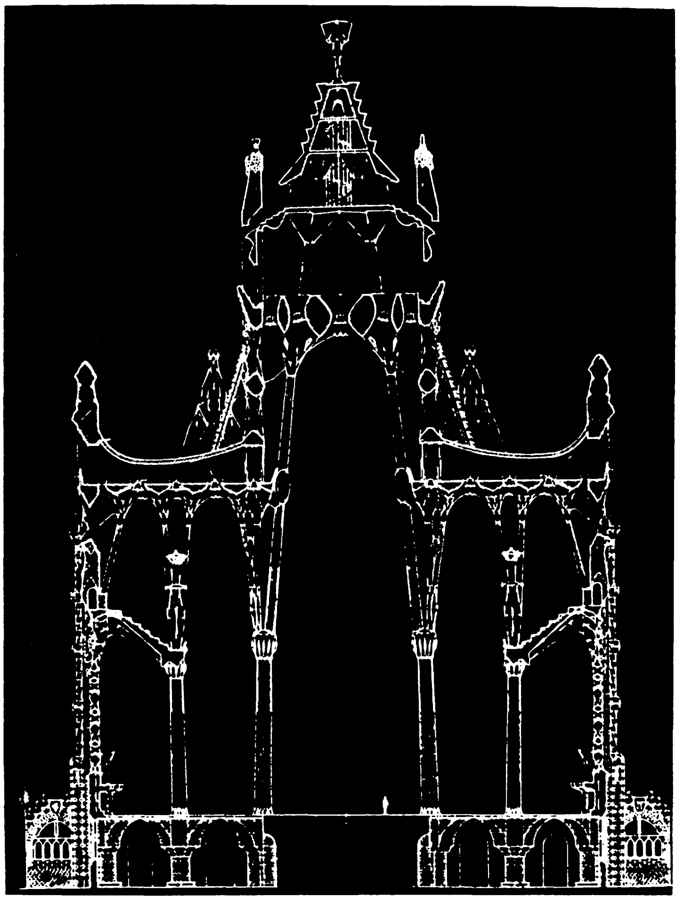


Fig.2-54. Barcelona: La Sagrada Familia.

Antonio Gaudi, the final version.

Arches and slant columns describe flow of lines of forces.

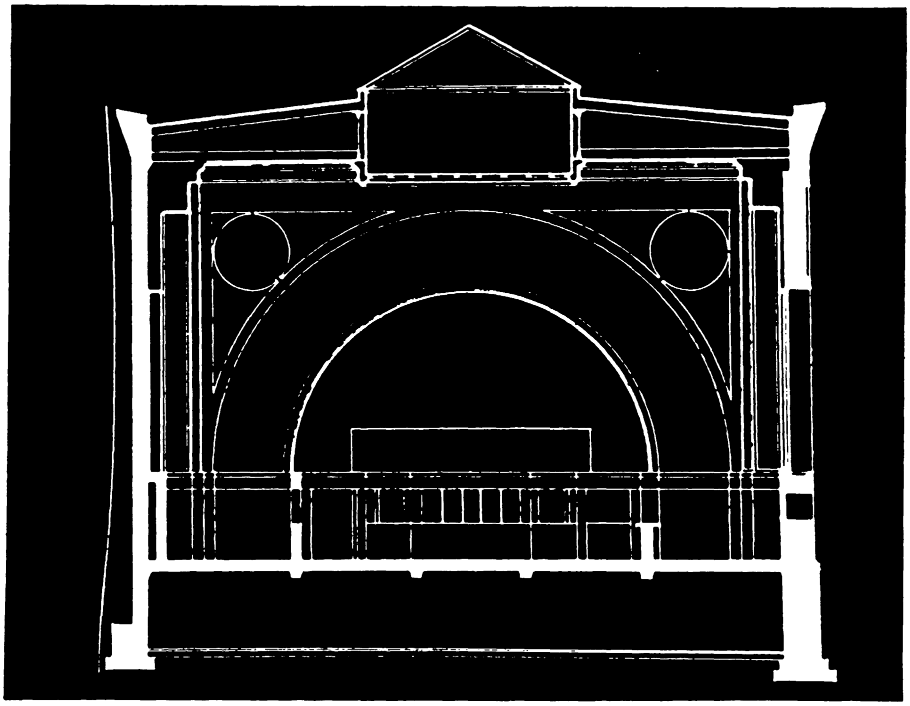


Fig.2-55. Minnesota: Farmers' Bank Owatonna. Louis Sullivan, 1907-1908. A cross section through the operational hall.

Fig.2-56. Bank Owatonna (compare Fig.2-55)
as commemorated by the US Post in 1982.

3. ARCH IN CONTEMPORARY ARCHITECTURE.

3.1. INTRODUCTION.

When the Ancient Greeks and Romans wanted to cover bigger spans, erecting their bridges, aqueducts or public buildings, they had no other means at their disposal and they had to apply arches. Contemporary materials like steel, laminated wood and to some extent prestressed concrete work in tension as well as in compression. Are then arches still so important elements in design, or do they play an exclusively decorative function only?

Searching for light constructions and economy in materials are the current requirements and therefore architecture depends upon engineering much more than ever in the past. Today utilization of material to its limit means not only better control of quality of that material, better technology - but first of all application of an improved construction. What makes the construction light and economical is correct distribution of loads, proper spreading of forces and possible elimination of bending moments. Arches may be designed in a way that bending is small or is completely eliminated and therefore they retain their importance in contemporary architecture.

An application of arches has changed in time and now arches are used in a variety of constructions. In addition to two-dimensional structures, arches are often designed for three-dimensional structures. The latter may be of frame or shell type. Modern arches are often combined with suspended systems. In reinforced concrete vaults and shells are considered economical and can cover considerable spans. New inflated arched constructions are used in industry, for sports halls etc. Application of new materials and improvement of traditional ones still open perspectives for arches.

The optimization of arches means the best selection of the shape and cross section as it has been discussed in chapter 1.5. New researches and theories attempt to define more precisely hazard of buckling, effects of dynamics of loading, vibration of the construction and fatigue of its materials.

Contemporary architecture with all its variety of trends and aesthetical approaches seems much more incoherent than the architecture of the past when particular styles prevailed. Also variety of technical and technological solutions influence the architecture of our times more than ever. New solutions are welcome in the search for originality. However, arches have retained their importance as structural and decorative elements.

This chapter will illustrate application of arches in contemporary architecture. Since the number of examples has to be limited, I have decided to select those which I found most representative and meaningful in different ways. I will certainly not stick to classification made in chapter 1.4.

The examples selected are presented in a sequence having in mind classical solutions, new constructions possible due to progress in technology and theory of structures, and finally decorative function of arches in contemporary architecture.

The descriptions will be as short as possible. Let the photographs, many of which I shot myself, speak for themselves.

3.2. CLASSICAL APPLICATION OF ARCHES IN ENGINEERING STRUCTURES.

It is difficult to determine a strict distinction of different systems. As a classical applications of arches I understand here the simplest forms of arches as basic elements in vertical engineering structures like bridges, horizontal structures in water dams and underground structures in the form of tube vaulting.

A classical arch superstructure consists of a deck or spandrel type, here illustrated with Maillard's bridge and Nosslachbrücke, or through type - represented by the Cincinatti bridge. A through-type arch is provided with a horizontal member between the supports, which acts like a tie of the arch.

A classical truss girder supported on arched superstructure is New River Gorge Bridge. In this case an arch is referred to as a trussed beam. The arch is not really curved beam, but consists of a series of straight members. The particular members are either in compression or in tension like in a simple horizontal truss.

The Hoover Dam represents a classical solution of an arch gravity dam. Its structural system exemplifies a pure arch action.

The Washington Metro system is another classical construction in the form of centuries old sewage collectors shape.

All these examples, even if referred to as classical, constitute achievements of contemporary architecture and engineering of the highest order.

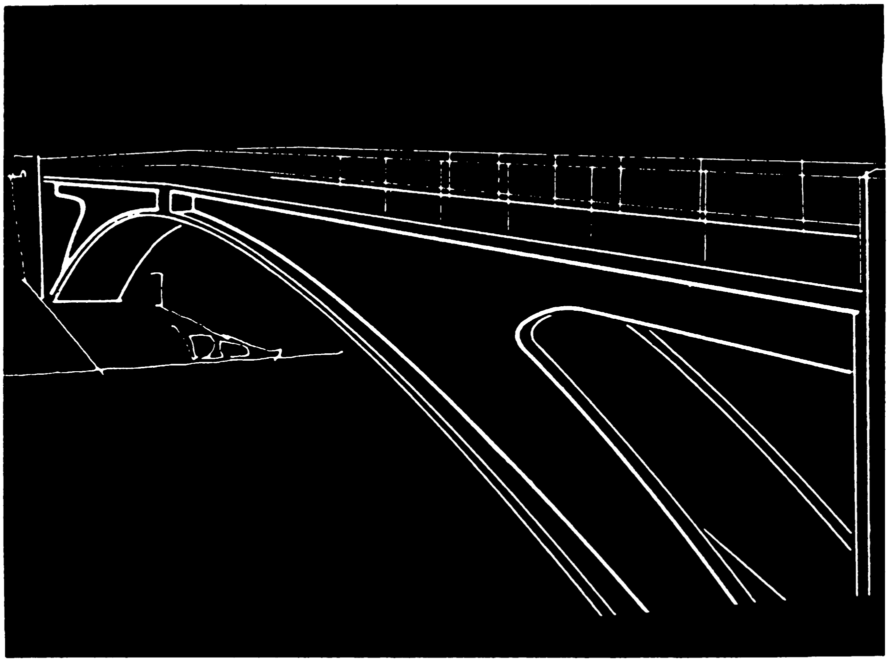


Fig.3-1. Three-hinged reinforced concrete bridge over the river Thur at Felsegg. Robert Maillard, 1933.

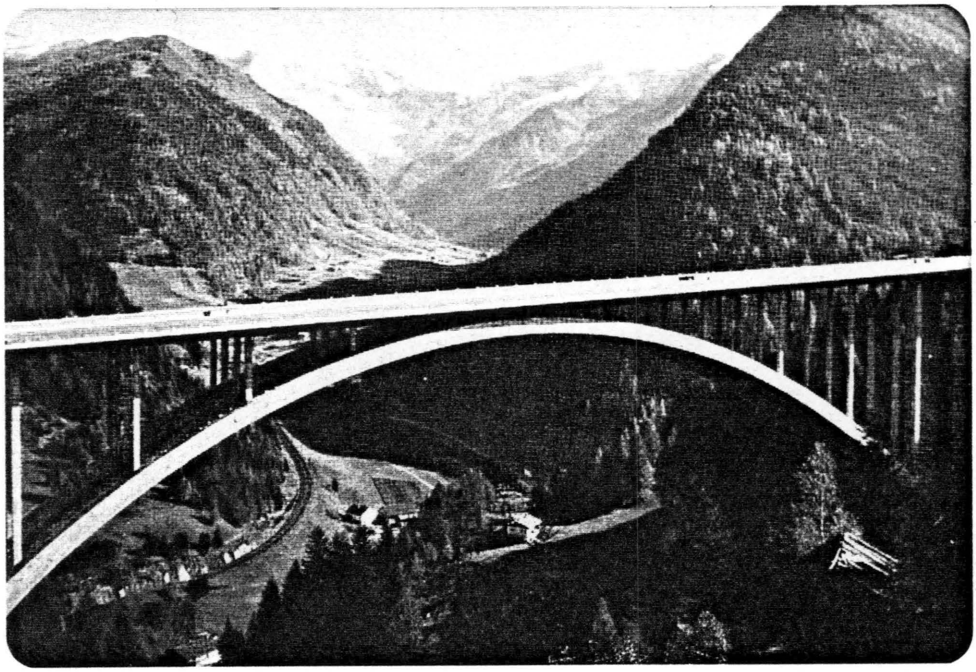


Fig.3-2. Tirol: Nosslachbrücke, 1970.

Reinforced concrete construction. Span 180 m.

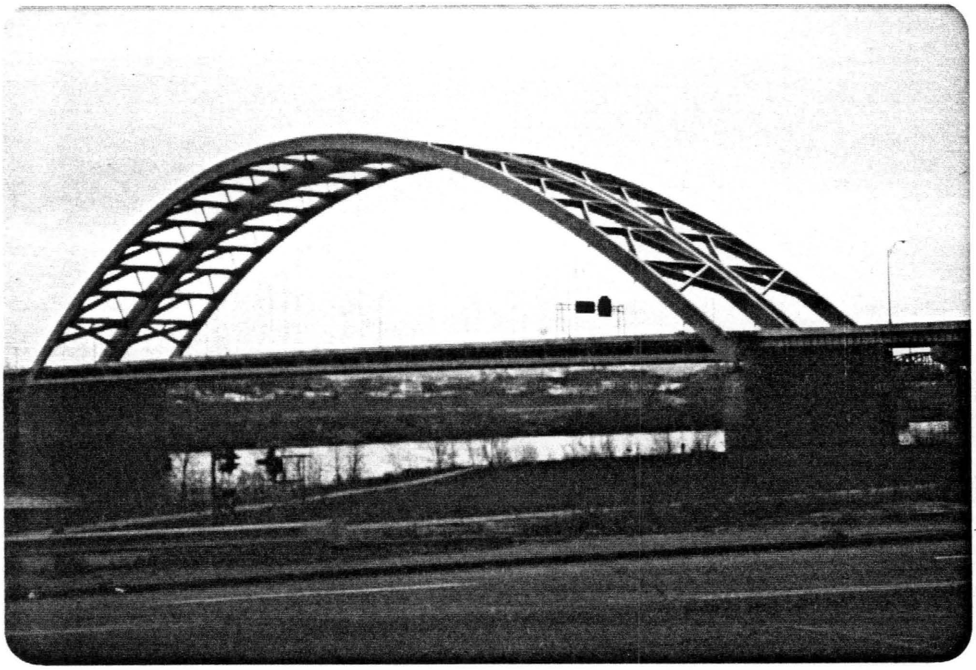


Fig.3-3. Cincinatti: Bridge over the Ohio River.

The arches stiffened with bracing. The lower part suspended.

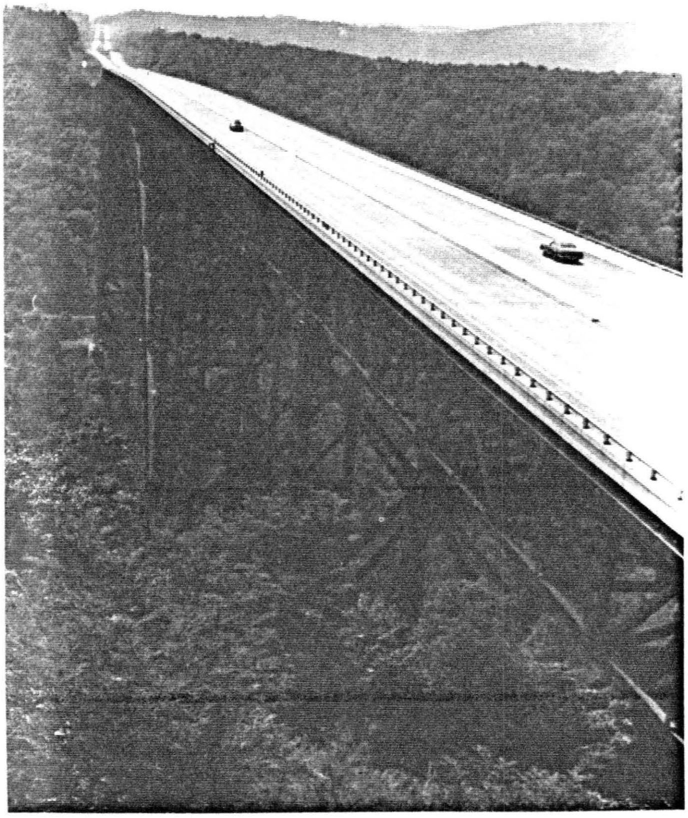


Fig.3-4. West Virginia: The New River Gorge Bridge. USS, 1977.

The longest single span arched bridge all over the world.

Fig.3-5. West Virginia: The New River Gorge Bridge.
Span of the arch 518 m. The road 267 m above the water.
The Cor-Ten steel used to prevent corrosion. Two-hinged arch
designed as a result of optimization study (chapter 1.5).

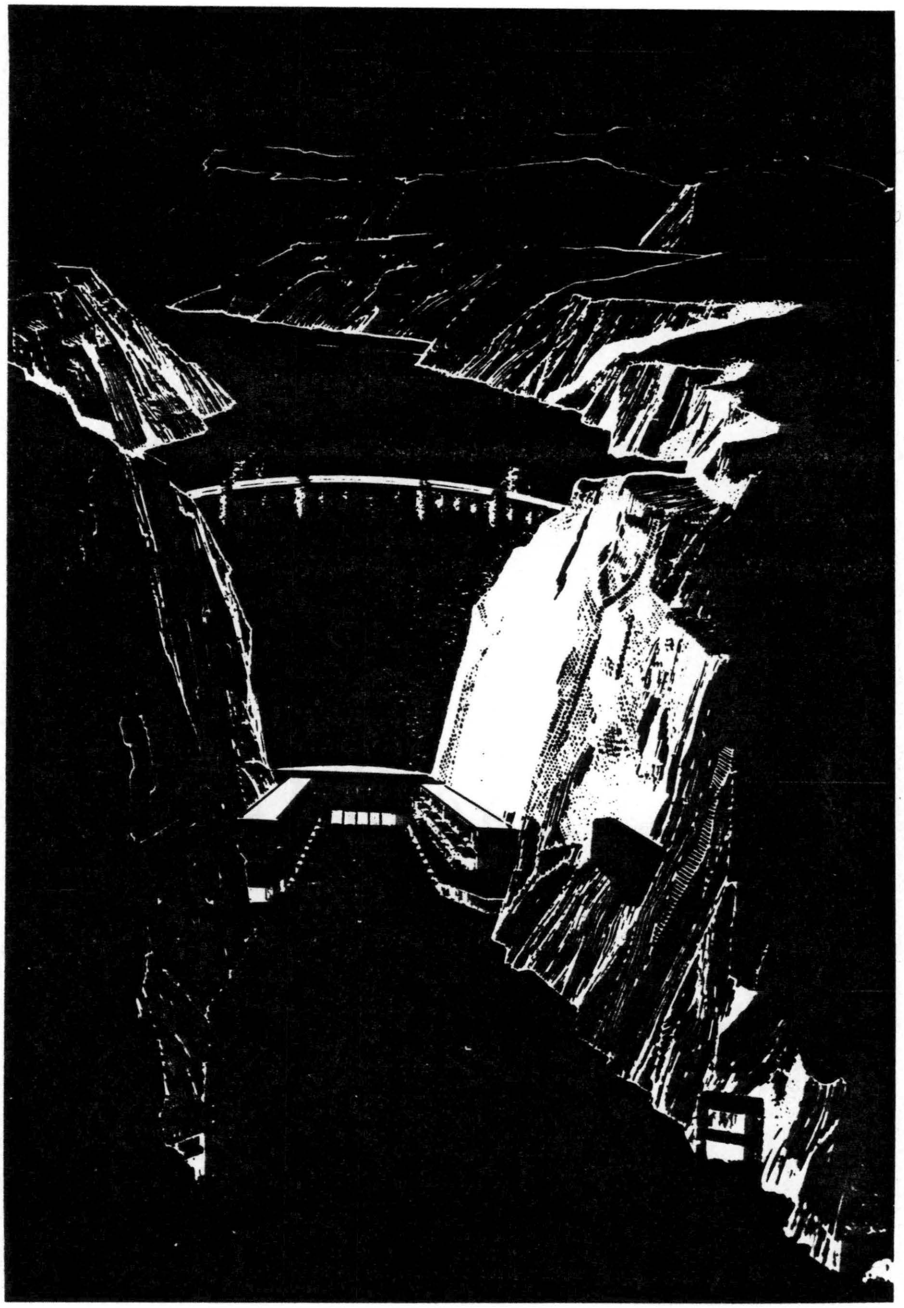


Fig.3-6. Black Canyon, Colorado: Hoover Dam built 1928-1936. Designed by John Lucien Savage, huge concrete construction is 221.6 m high with its crest length of 360.3 m.

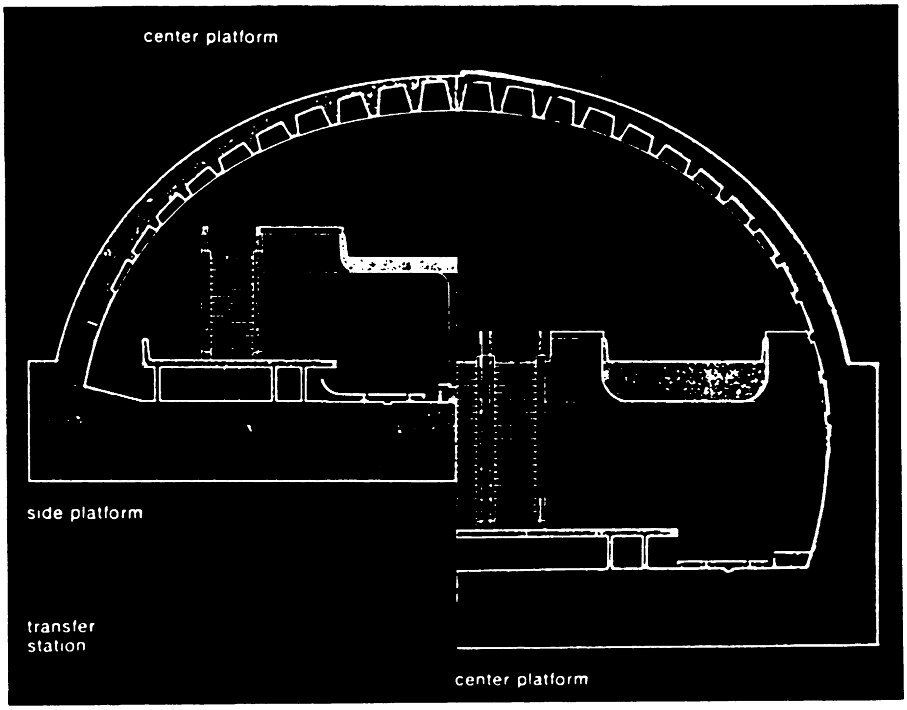


Fig.3-7. Washington D.C.: Metro transfer station. Constructed by Harry Weese & Assoc. in the 70's exemplifies economical and beautiful application of reinforced concrete.

3.3. EXAMPLES OF NEW TECHNOLOGY IN ARCH CONSTRUCTIONS.

It is difficult to overestimate the impact of modern technology on architecture. If we mention only new synthetic and improved traditional building materials, new technological solutions, prefabrication - we see how much happens when compared to technological progress in the past centuries.

An invention of laminated wood has made it possible to apply that material for arches.

A progress in pre- and poststressing opens a way for design of arches more resistant than ever to bending.

There are almost unlimited possibilities of an application of the thin shaped concrete shells.

The new synthetic materials open new perspectives for inflated arches, domes and other constructions.

It seems also evident that the prefabrication will provide new applications and perspectives for arches.

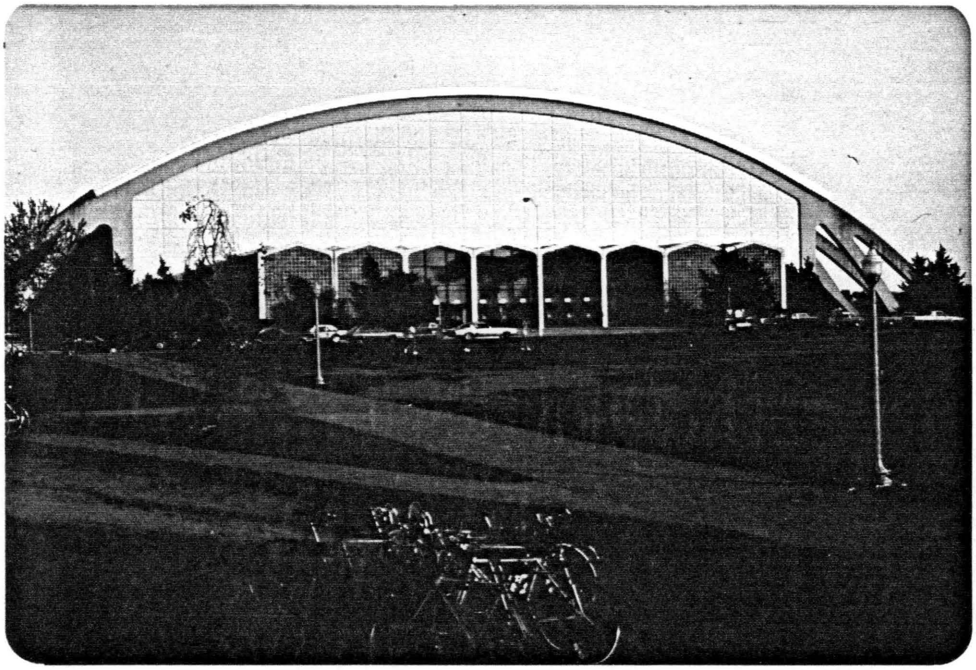


Fig.3-8. Blacksburg VA.: 10,000 seat VPI Coliseum. Laminated wood arches spanning the distance of 67.36 m. The only longer wooden arch construction (L=68.28 m) exists in Florida and has been built quite recently.

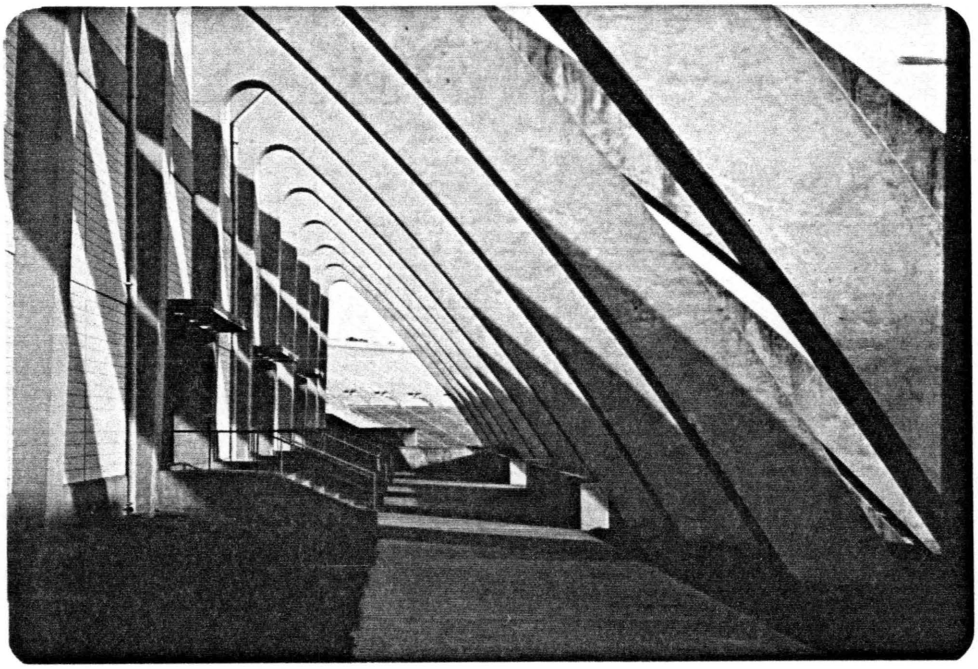


Fig.3-9. Blacksburg VA.: Coliseum. Reinforced concrete buttresses absorb thrust from wooden laminated arches.

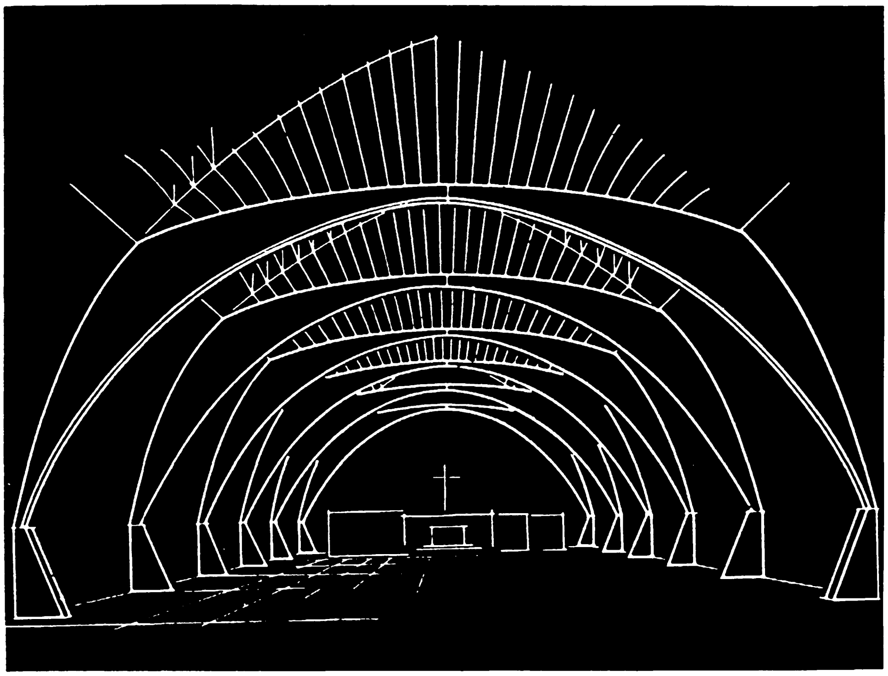


Fig.3-10. Three-hinged arches in laminated wood.

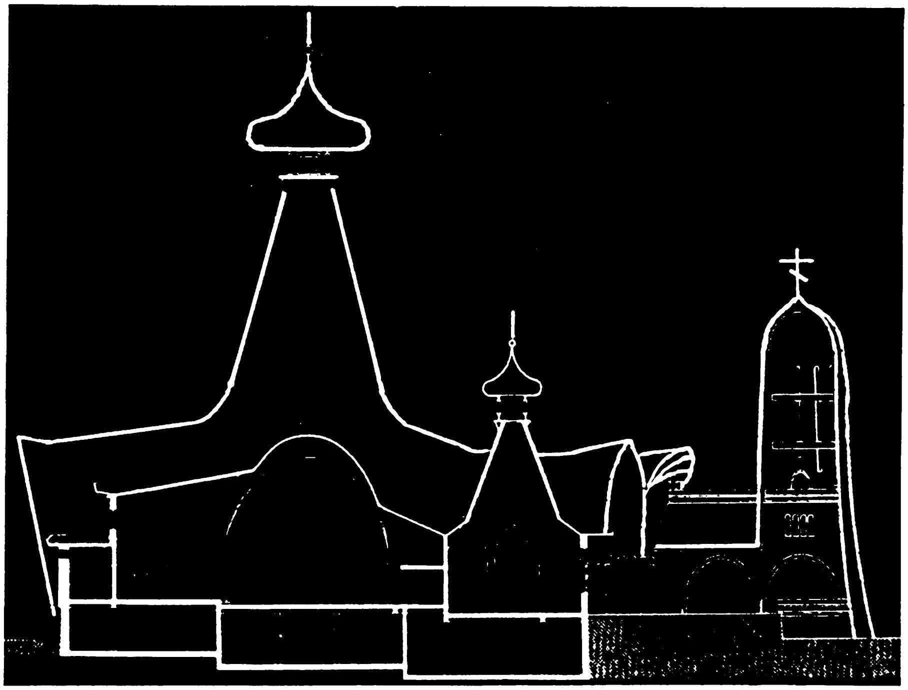


Fig.3-11. Hajnówka, Poland: An Orthodox church constructed in ferro-cement by Aleksander Grygorowicz, 1979. An application of shells still opens perspectives for architectural design.

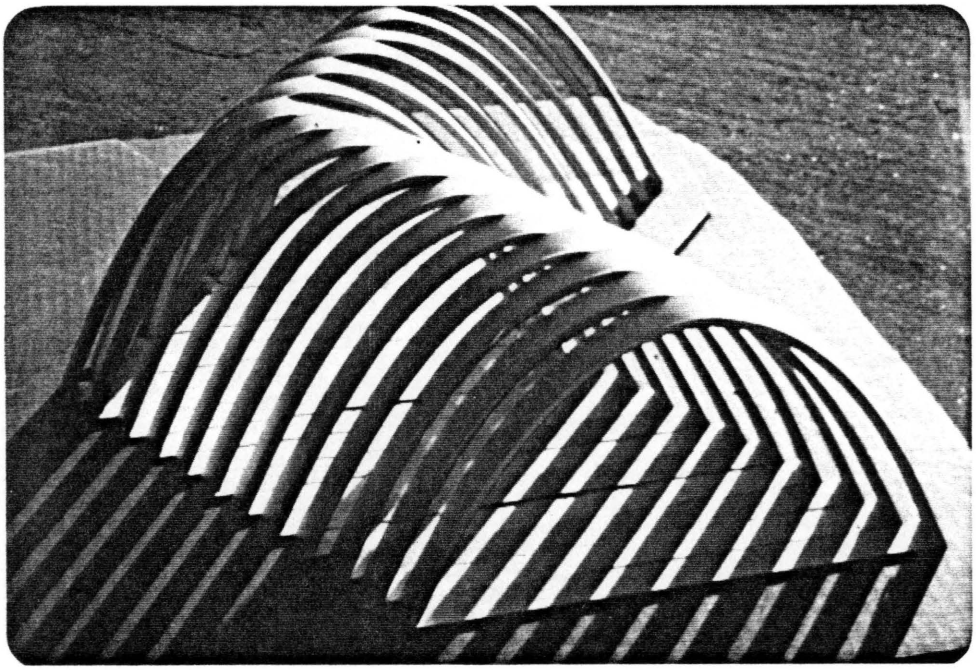


Fig.3-12. Blacksburg, Virginia Tech. Exhibition hall designed by the author of this thesis in the process of graduate studies. Arches prefab or cast-in-situ (typical formwork).

3.4. EXAMPLES OF ARCHED CONSTRUCTIONS.

Some structural forms of arches have been discussed in chapter 1 and are shown in Fig. 1-35.

Generally speaking new structural forms of arches mean modification of shapes, and new applications in variety of constructions.

The two-dimentional application of arches with the depth of their cross sections in accordance with the diagrams of bending moments can be illustrated with Roma Termini Railroad Station (Fig. 3-13).

A correct solution, how the dome should meet the ground has been designed by Nervi in his Sports Palace. The supports following closely the lines of forces succesfully eliminate bending in the entire construction (Fig. 3-14).

Other three-dimensional actions of arches are here illustrated by works of Kahn (Fig. 3-15), E. Saarinen (Fig. 3-16) and Utzon (Figs. 3-17 to 3-19).

A combination of arches with suspended systems can provide economical and interesting architectural solutions (Fig. 3-20).

At the end of this short survey, examples of arched trusses are shown in figures 3-21 and 3-22.

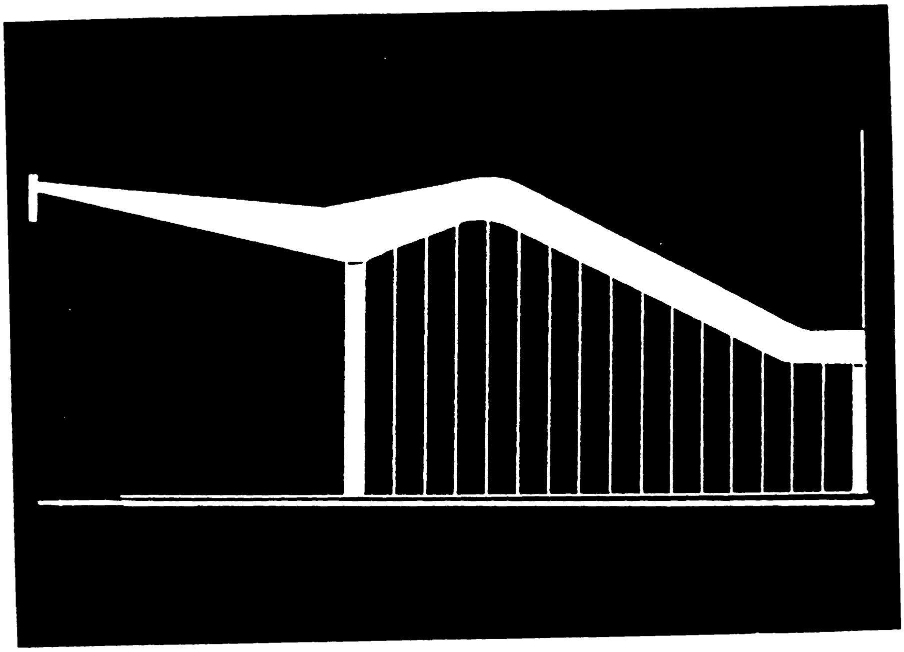


Fig.3-13. Rome: Termini Statione.

Eugenio Montuori & others, 1948-1951.

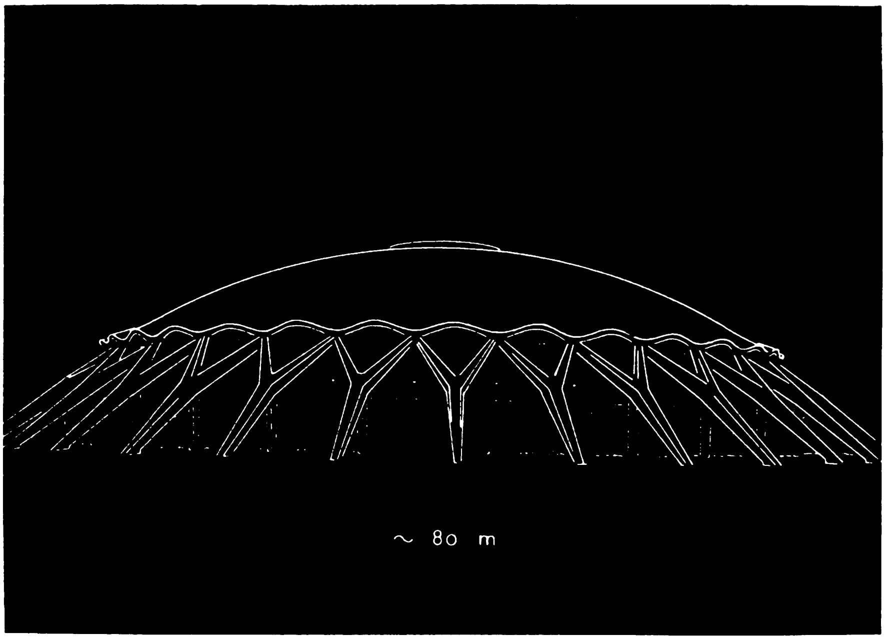


Fig.3-14. Rome: Sports Palace. Luigi Nervi, 1960.

The ribbed dome in reinforced concrete

looks even more impressive and beautiful from inside.

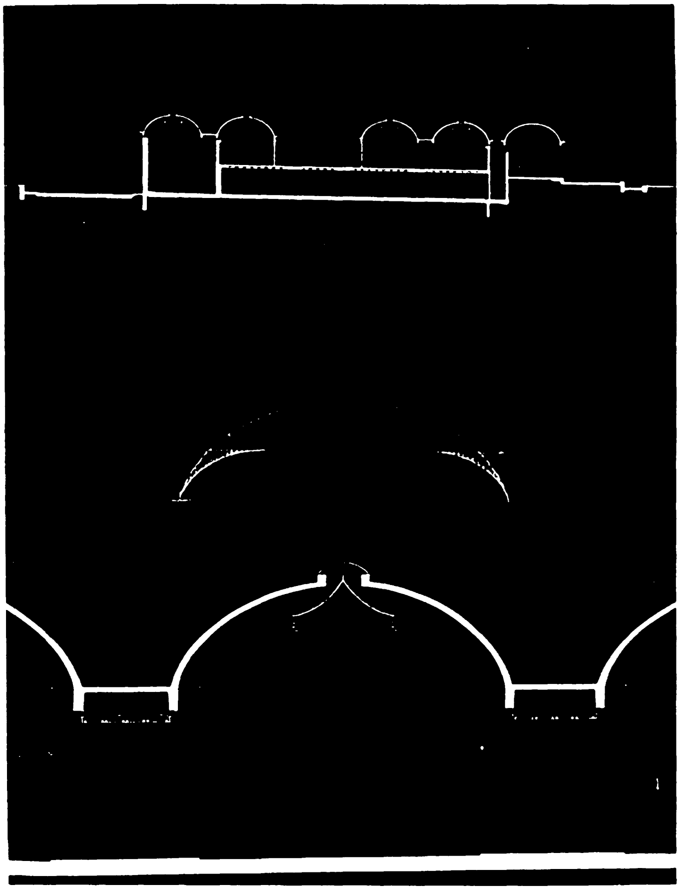


Fig.3-15. Fort Worth, Texas: Kimbell Art Museum. Louis Kahn, 1972. Interesting application of arches working as cylinder-shaped shells.

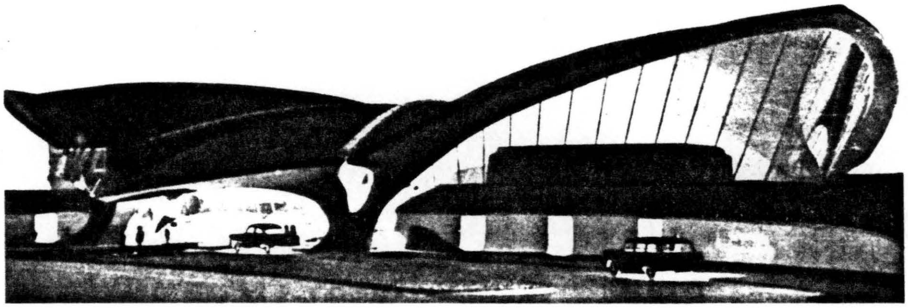
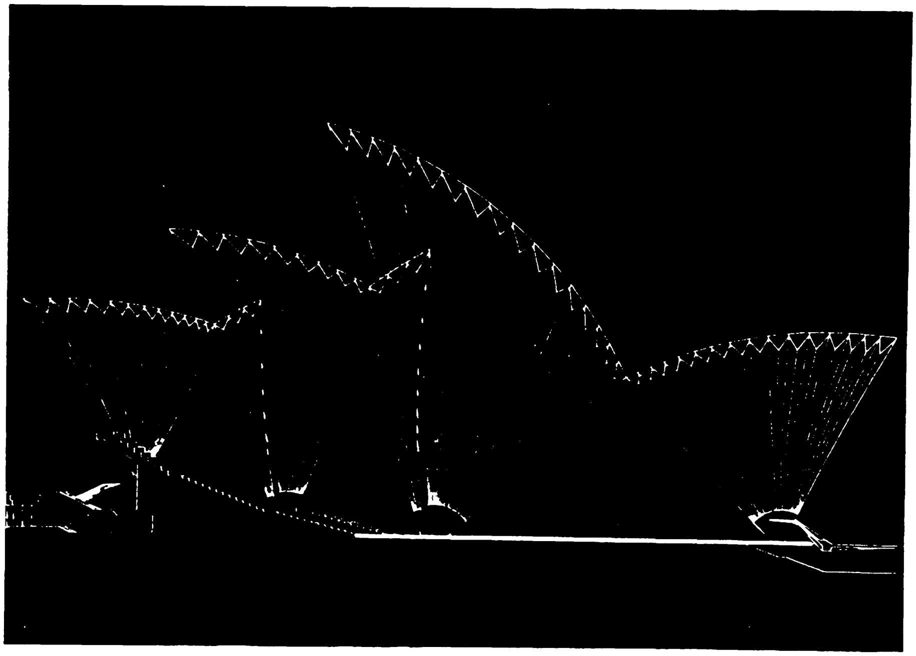
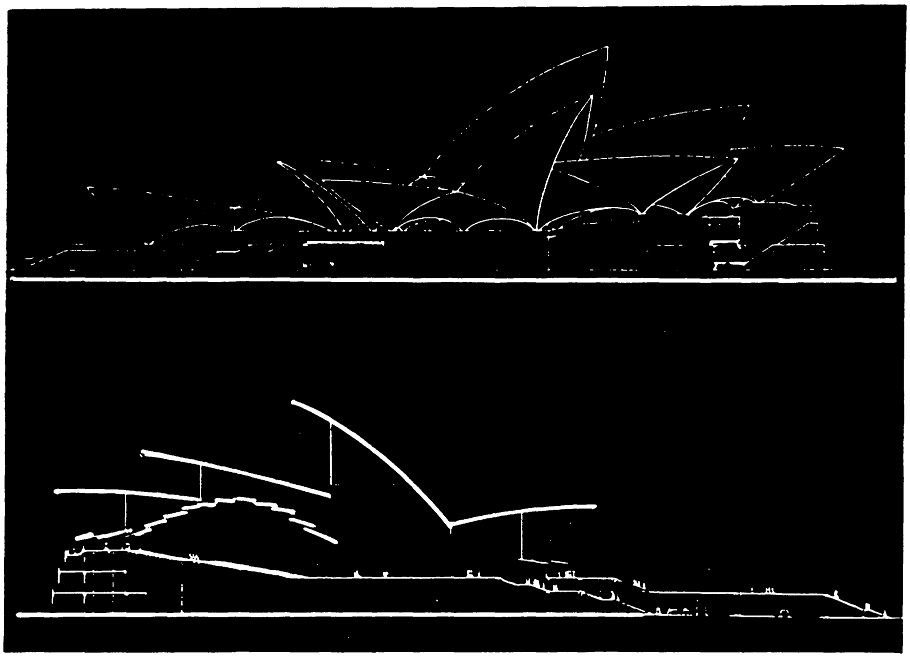


Fig.3-16. New York, New York: John F. Kennedy Airport.

TWA Terminal. Earo Saarinen, 1956-1962.





Figs. 3-17 and 3-18. Sydney: Opera House.

Jorn Utzon 1957-1970. Great shapes which do not necessarily provide optimal accoustical performance.

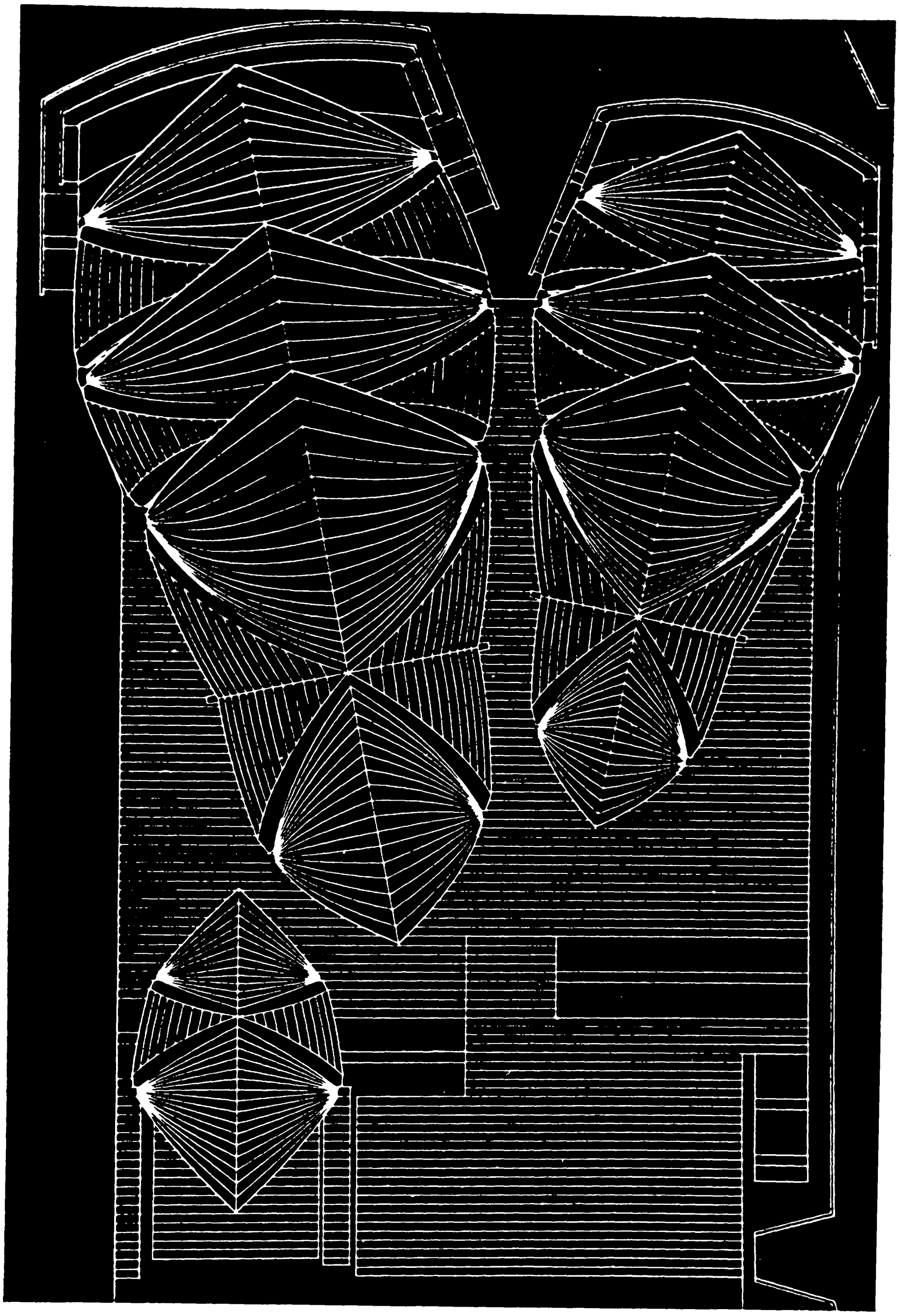


Fig.3-19. Sydney: Opera House. Bird's-eye view of the shells.

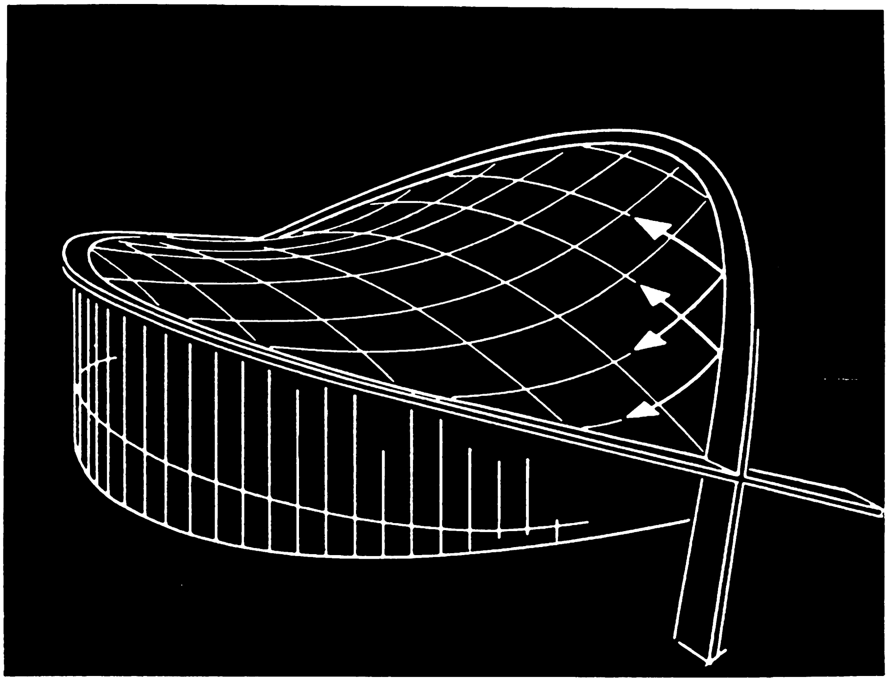


Fig.3-20. Raleigh, North Carolina: Sports Arena. Mattew (Maciej) Nowicki, 1948-1950. First suspended construction applied in public building all over the world. Nowicki, before settled in the United States, had taught in Polytechnic University of Warsaw and participated in the post-war reconstruction of Warsaw.

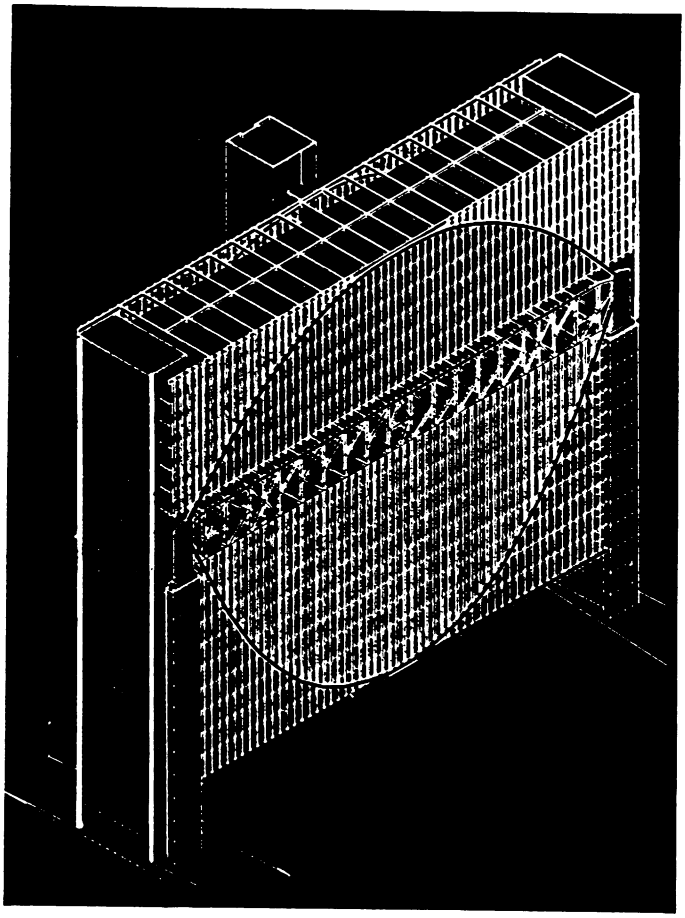


Fig.3-21. Minneapolis, Minnesota: Federal Reserve Bank. Gunnar Birkerts, 1973. In the first phase, the suspended construction has been completed. It is interesting to note, that the horizontal component forces of the arch and of the suspended construction have opposite directions.

Fig.3-22. Warsaw: Central Railroad Station. Arseniusz Romanowicz, 1972-1976. The roof construction consists of 16 light prefab steel arched trusses with relieving cantilevers on both sides.

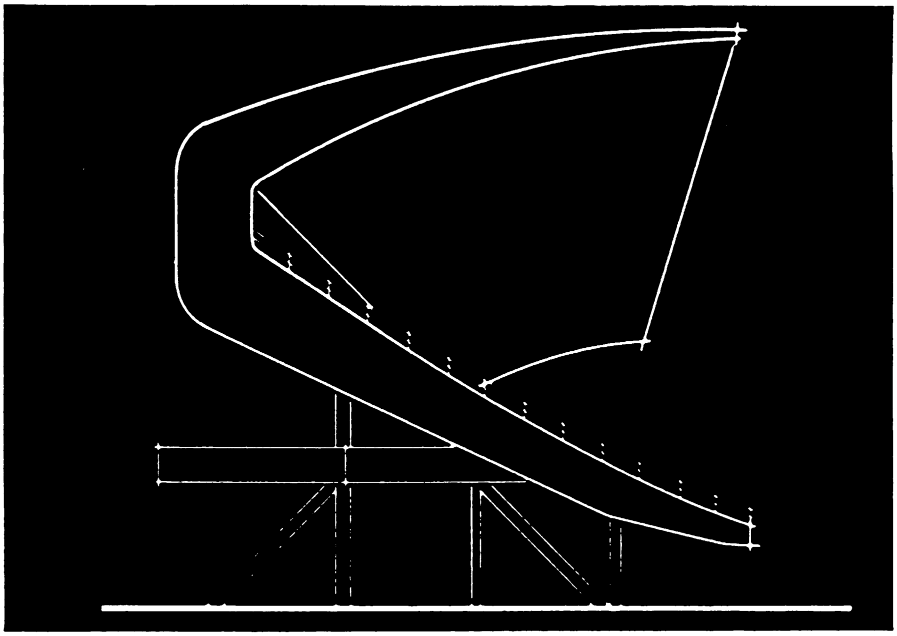


Fig.3-23. Caracas: Reinforced concrete tribune, span 25 m

Carlos Raul Villanueva, 1950-1951.

Even if the construction does not represent a pure form of arch it is an interesting example of curved shape shell.

3.5. EXAMPLES OF ARCHES AS DECORATIVE ELEMENTS.

Except of pure sculptural elements it is difficult to distinguish arches as decorative elements only. Architecture means complexity of buildings so their elements have to fulfil demands of the construction, function, organization of space, ensure acoustical performance etc. Most of the architectural elements serve multiple purposes.

The form may mean an expression of actually prevailing aesthetic trends and styles, an impact of the vernacular architecture, or simply an individual taste and imagination. The individualities of great architects have created patterns followed by others, but many outstanding, original artists have become isolated and misunderstood.

Aalto's asymmetric arches, Wright's spiral Guggenheim Museum, Le Corbusier's arches and oval shapes were accepted from the very beginning, influencing a number of architects, including talented ones, like Eero Saarinen, Richard Meier and others. On the other hand the magnificent arches of Gaudi almost till today have remained undiscovered.

A couple of examples given in this chapter will certainly not constitute an organized survey, which could provide an opportunity for a separate research.

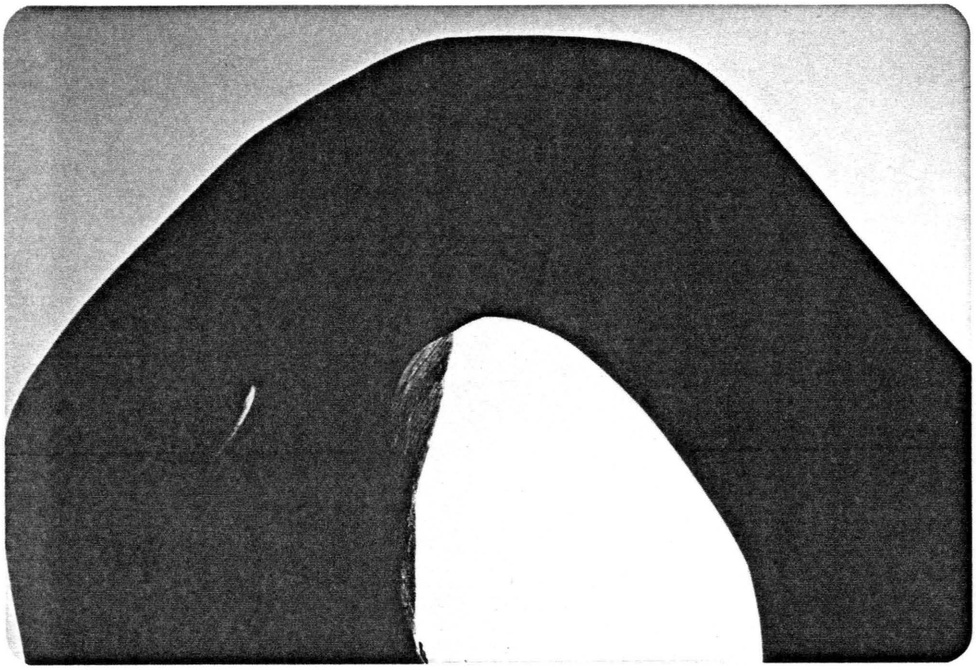


Fig.3-24. Columbus, Indiana: Arch sculptured by Henry Moore, 1971.

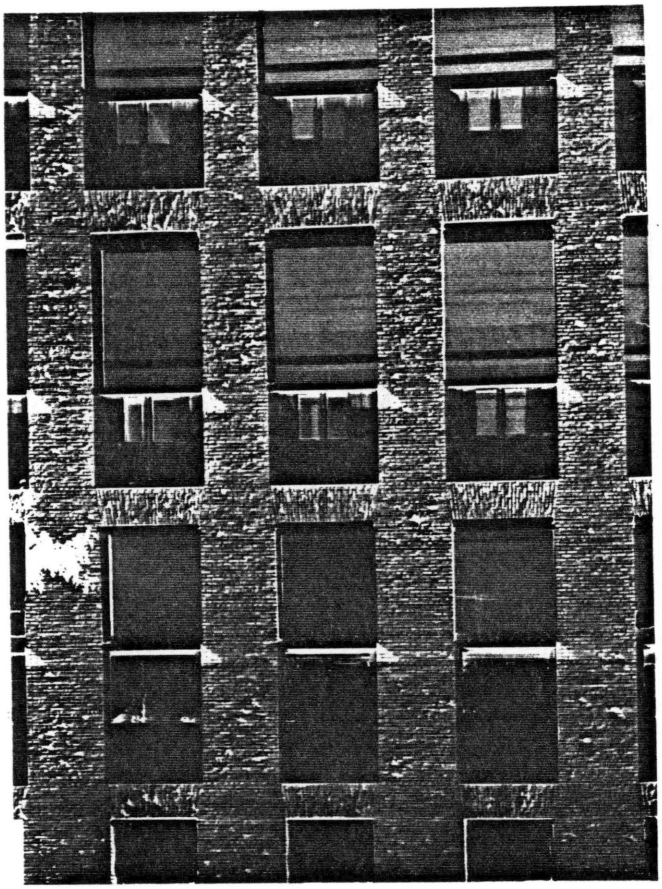


Fig.3-25. New Hampshire: Exeter Library. Louis Kahn, 1972.

An interesting application of jack arches.

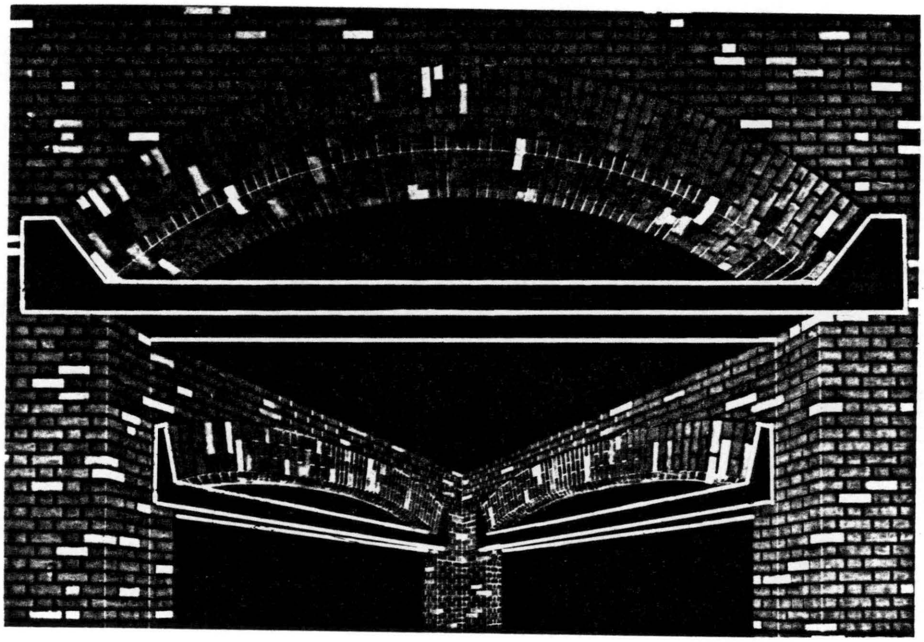


Fig.3-26. Ahmedabad: Indian Institute of Management.

Louis Kahn, 1963.

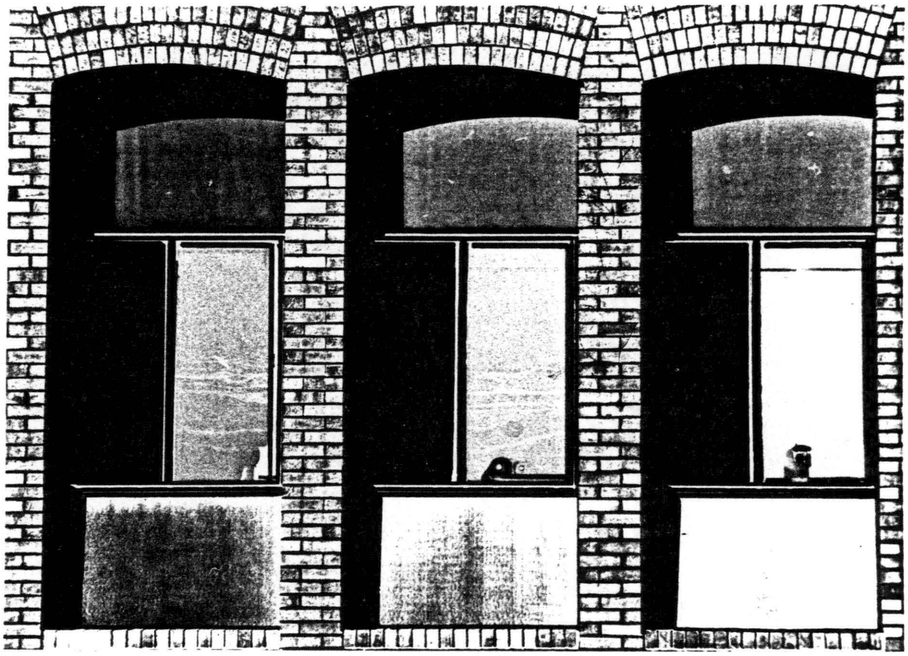


Fig.3-27. Columbus, Indiana: Northside Junior High School.

Harry Weese, 1961.

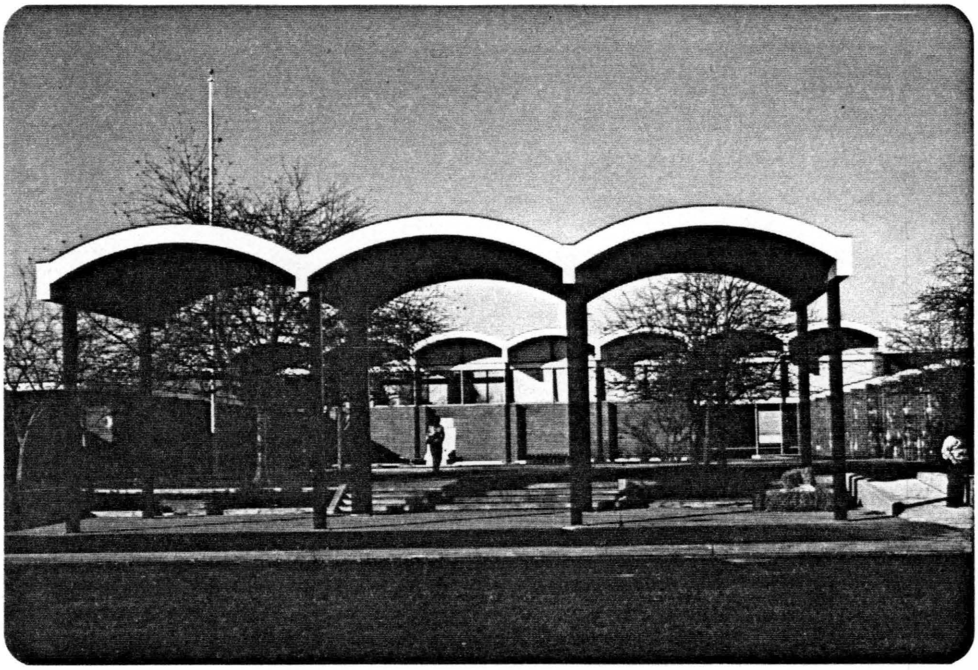


Fig.3-28. Columbus, Indiana: Parkside Elementary School.

Norman Fletcher, 1962.

The arches have not only become a symbol of the school; they also provide a shelter against rain and snow.

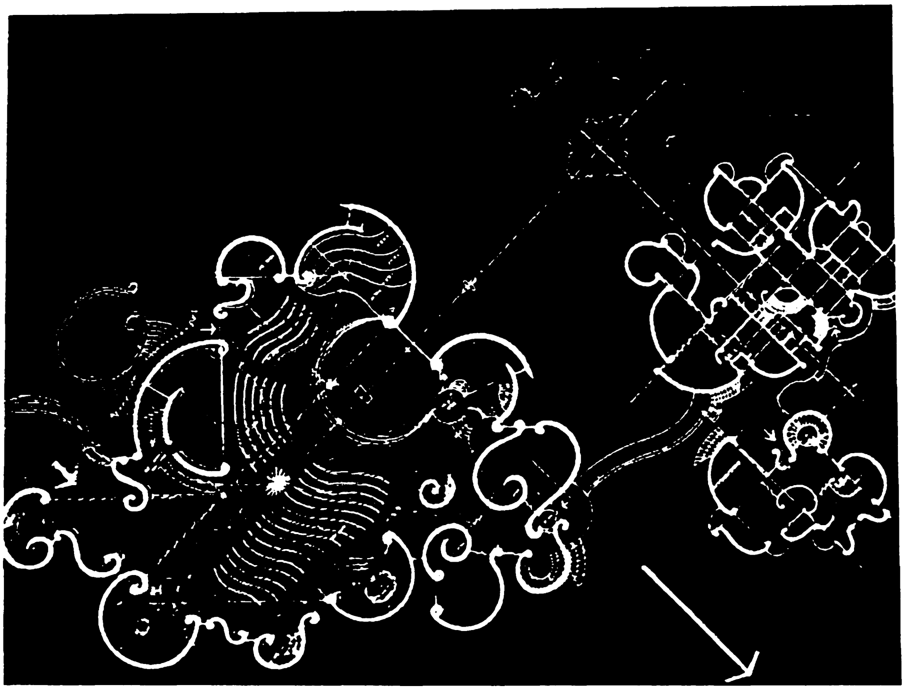


Fig.3-29. Katowice, Poland: Church in the Tysiaclecie Estate. Henryk Buszko, Aleksander Franta, 1978. The cylindrical walls provide stiffness and interesting appearence of the interiors and from the outside.

3.6. CONCLUSION.

The arch as an expression in contemporary architecture... This thesis abounds in photographs which illustrate the importance of the arch in architecture as a structural, functional, and decorative element in modern buildings and constructions. I have been happy to work on arches. These studies fascinated me. For the conclusion of this work I have presented several photographs, the photographs taken by me in Warsaw during my last visit there in summer 1981.

Warsaw, completely destroyed by Hitler's Nazies during the Second World War, has been rebuilt. The process of reconstruction was considered not only as proof that the Polish nation still existed and had the right to exist, but as a manifestation of the Polish peoples relation to their past, to their national heritage and culture. It was not considered simply as a fulfilment of a tremendous need for housing either, because it would have been much cheaper and faster to erect concrete or glass-box buildings instead of reconstructing mediaeval ones. Their architects met the social demands. They have completed tremendous work, often without salaries and gratuities. All the best Polish architects joined the reconstruction project with professors of the Polytechnic University of Warsaw - Jan Zachwatowicz, Jan Bogusławski, Bohdan Pniewski, and many others. Their studies were based not only on documentation of old buildings, photographs and historical analysis - but even old sketches and canvas, including famous works of Bernardo Bellotto (Canaletto) were used. It has been understood that the architecture, whatever we call it, modern or traditional, progressive or

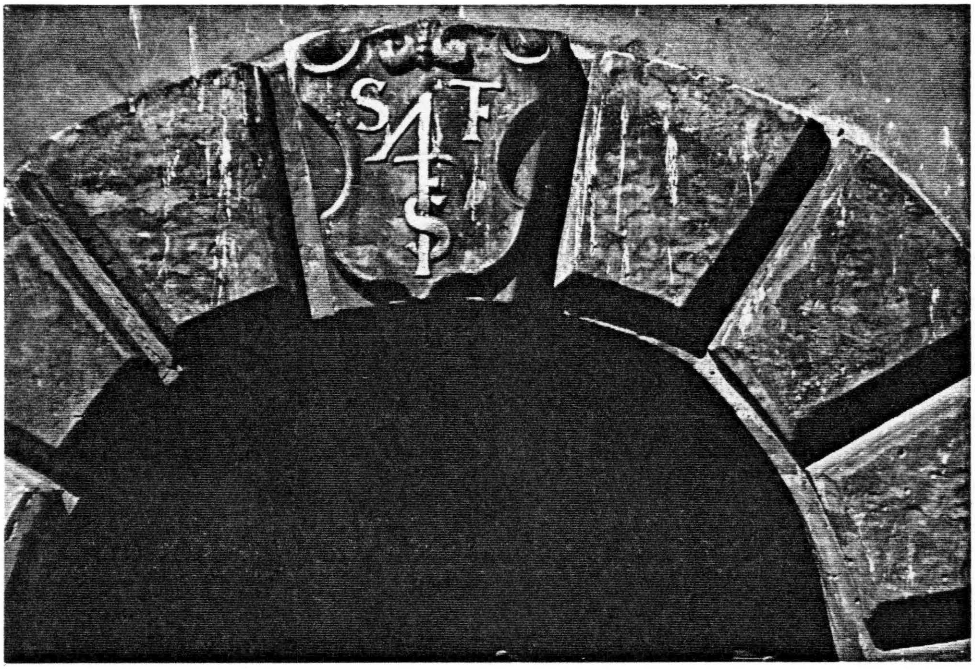


Fig.3-30. Warsaw: Old Town. The Falkiewicz House.

Remodelled in 1643; reconstructed in 1951-1953.

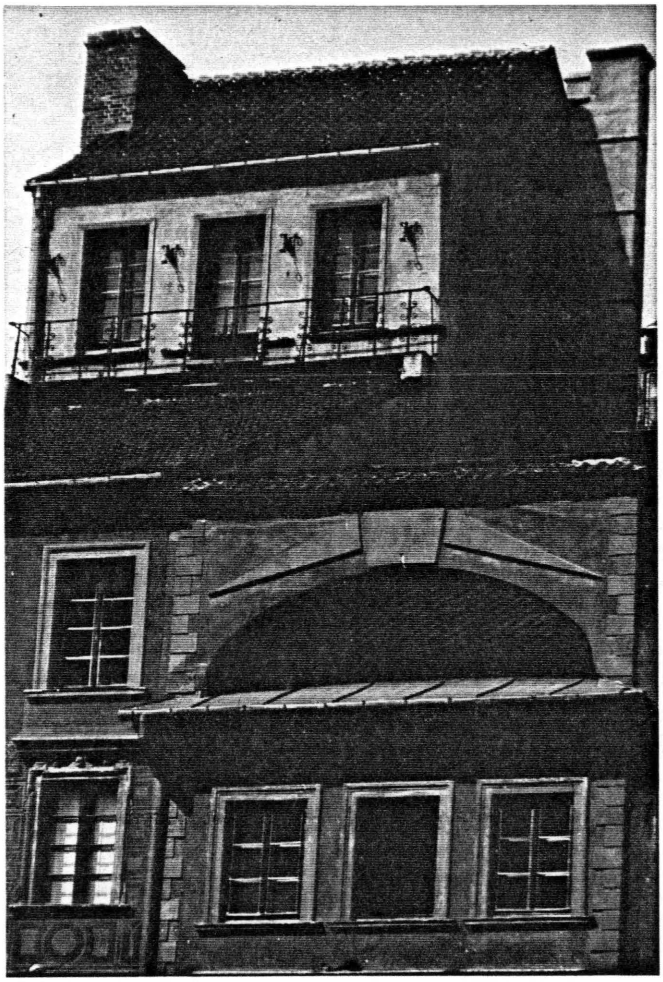


Fig.3-31. Warsaw: Old Town Market Square. Kleinpoldt's House. The straining arch over the surmounting cornice, 1788; renovated 1950-1953.

Fig.3-32. Warsaw: Old Market Square. Balcer's House. 17th-century portal preserved against the background of an arcade and remains of a Gothic wall. Reconstructed in 1952-1953, the building now is housing the Adam Mickiewicz Museum of Literature.

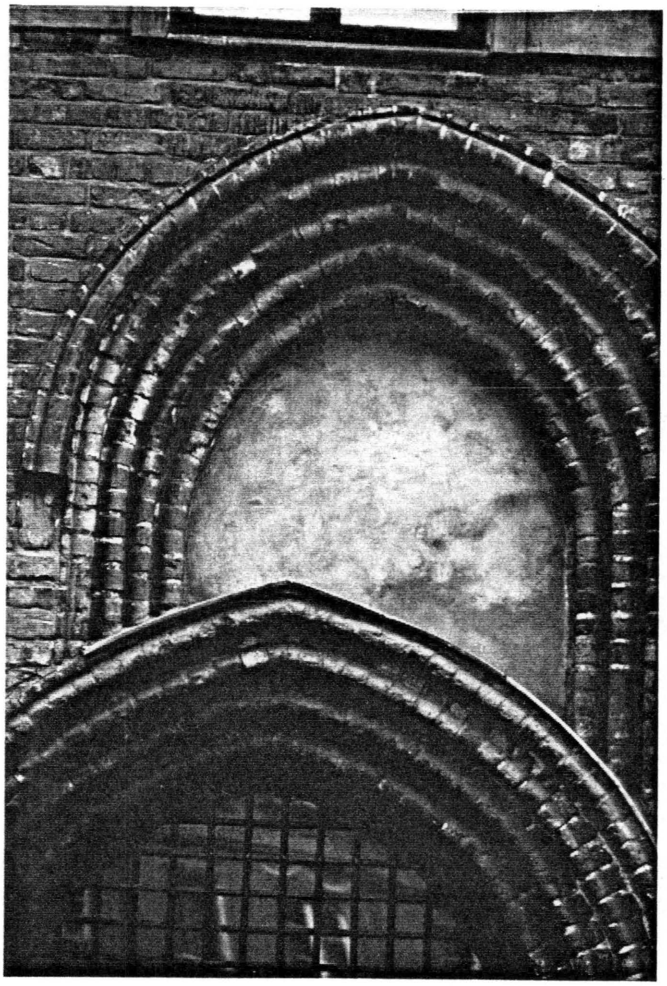


Fig.3-33. Warsaw: Old Town Market Square.

The Wilczek's House. Raised in the early 16th century.

A Gothic portal exposed in 1928; reconstructed in 1952-1953.

conservative, even if designated to the future, is a continuation of the past and of our cultural heritage. And that is why I see our old but new Varsovian arches as a very personal, important and unique expression of contemporary architecture.

For the same reason I do not put a sign of equation between a modernity and a search for new and original forms. I understand modernity as our conscious relation to the surrounding world, as an understanding of its problems, ability of forseeing needs and developments anticipated in the future. The future from which the past should not and cannot be eliminated.

Moving towards the future we witness the continuous process of changes. As I tried to show in the preceeding pages the development of the arch throughout the centuries has continuously brought new structural, functional and aesthetical solutions. It is difficult to predict precisely what the future arches will be due to the further progress in the technology and design processes, new architectural styles and social demands; but one can state with certainty that all new solutions will be based on the passed experience and the continuity of development.

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5. GLOSSARY.

ABUTMENT, the solid part of a pier from which the arch immediately springs. Abutments are artificial or natural: the former are usually formed of masonry, concrete, etc., and the latter are the rock or other solid materials on the banks of the river, in the case of a bridge, which receive the foot of the arch.

AISLE, the side subdivision in a church, usually separated from the nave or the center division by pillars or columns and covered with separate vaults.

AMBULATORY, a sheltered place for exercise in walking; a cloister.

ARC, In geometry, a portion of a circle or other curve line. The arc of a circle is the measure of the angle formed by two straight lines drawn from its extremities to the center of the circle.

ARCH, curved support over the space or opening; in masonry a mechanical arrangement of blocks disposed in the line of some curve, and supporting one another by their mutual pressure and forces of friction.

ARCH PERIMETER, the boundary of an arch.

ARCHWAY, an aperture in a building covered with a vault; an arched passage or gate.

ARCUS ECCLESIAE, in mediaeval architecture, the arch dividing the nave of the church from the choir or chancel.

AXIS OF ARCH, a line passing through the center of gravity of particular cross sections.

BUTTRESS, a mass of brickwork or masonry to support the side of a wall of great height and to absorb the thrust; also mass of concrete pressed on the opposite side by a bank of earth or body of water. Buttresses are commonly employed against the piers of Gothic buildings to resist the thrust of the vaulting.

CAMBER, an arch on the top of an aperture or on the top of a beam.

CORBELED ARCH, an early form of the arch with a range of projecting stones.

CORE OF SECTION, central part of the cross section; in rectangular cross section central one-third. When the resultant force acts within the core of section bending does not occur.

COVE, any kind of concave moulding or vault; the term, in its usual acceptation, is the quadrantal profile between the ceiling of a room and its cornice.

CROSS VAULTING, that formed by the intersection of two or more simple vaults. When each of the simple vaults rises from the same level to equal heights, the cross vaulting is denominated a groin.

CROWN OF AN ARCH, the most elevated line or point that can be assumed in its surface.

DOME, the spherical, or otherwise formed, convex roof over a circular or polygonal building. A surbased or diminished dome is one that is segmental on its vertical section, a surmounted dome is one that is higher than the radius of its base.

EXTRADOS, the exterior curve of an arch. The term is generally used to denote the upper curve of the voussoirs or stones which immediately form the arch.

FLYING BUTTRESS, a buttress in the form of an arch, springing from a solid mass of masonry, and abutting against the springing of another arch which rises from the upper points of abutment of the first.

GROIN, the line formed by the intersection of two arches, which cross each other at any angle.

HAMMER BEAM, a beam acting as a tie at the feet of a pair of principal rafters, but not extending so as to connect the opposite sides. Hammer beams are used chiefly in roofs constructed after the Gothic style, the end which hangs over, being frequently supported by a concave rib springing from the wall, as a tangent from a curve, and in its turn supporting another rib, forming an arch. The ends of hammer beams are often decorated.

HAUNCHES OF AN ARCH, the parts between the crown and the springing.

HEIGHT OF AN ARCH, the distance between the level line of the springing to the intrados.

HORIZONTAL PROJECTION OF A VAULT, the projection made on a plane parallel to the horizon. This may be understood perspectively, or orthographically, according as the projecting rays are directed to a given point, or perpendicular to a given point.

INTERCEPTED AXIS, in conic sections, that part of the diameter of a curve comprehended between the vertex and the ordinate. It is also called the abscissa, and forms an arch of a peculiar kind.

INTERLACING ARCHES, arches, as in an arcade, the mouldings of which intersect each other, as frequently seen in Gothic buildings.

INTRADOS, the interior and lower line or curve of an arch.

INVERTED ARCH, one wherein the lowest stone or brick is the keystone. It is used in foundations, to distribute the weight of particular points over the whole extent of the foundation.

JOINTS, the seams or planes, in which two adjacent voussoirs are united.

KEY STONE, the highest or central stone of an arch.

LINTEL, a horizontal element over a door, window, or other opening to discharge the superincumbent weight.

PENDENT, an ornament suspended from the summit of Gothic vaulting, very often elaborately decorated.

PIER, the solid support from which an arch springs. In a bridge, the pier next the shore is usually called an abutment pier.

POINTED ARCH, an arch sharply (lancet) pointed and lofty in proportions to its span.

RADIUS OF CURVATURE, the radius of the osculatory circle at any point in a curve.

RELIEVING ARCH, an arch over a lintel or other construction; the relieving arch takes most of the load.

RISE, height of an arch above the line connecting supports.

SEGMENTAL ARCH, an arch shaped as a part cut off from circle, ellipse, etc.

SKEWBACK, in a jack or curved arch, that part of it which recedes beyond the springing from the vertical line of the opening.

SOFFIT, the lower surface of a vault or arch.

SPAN, the distance between the piers or abutments. An imaginary line across the opening of an arch or vault, by which its extent is estimated.

SPANDREL, the irregular triangular space between the outer curve or extrados of an arch, a horizontal line from its apex, and a perpendicular line from its springing.

SPRINGER, the impost or place where the vertical support to an arch terminates, and the curve of the arch begins; the term is sometimes used for the rib of a groined vault.

STILTED ARCH, a portion of masonry above the regular column, which is constructively part of the pier, but in the direction assumes the form either of a portion of the arch or of a distinct member.

TIE, a timber-string, iron or steel rod connecting two bodies together, which have a tendency to diverge from each other, such as tie-beams, diagonal ties, truss-posts, etc.

THRUST, the force exerted by any body or system of bodies against another. Thus the thrust of an arch is the power of the arch elements considered as a combination of wedges to overturn the abutments or walls from which the arch springs.

VAULTING SHAFT, a pillar, sometimes rising from the floor, or only from the capital of a pier, or even only from a corbel, from the top of which spring the vaulting ribs of the groining.

VOUSSOIRS, a wedge-like stone or another matter forming one of the pieces of an arch. The center voussoir is called a keystone.

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ARCHES IN ARCHITECTURE

by

Jerzy Andrzej Starczewski

(ABSTRACT)

The idea of the arch as a compression member is presented. The statical work of the arch is illustrated with experiments on photoelastic models. The search for optimal shapes of arches is discussed.

A study includes historical development of the arch from the Sumerian times up into the XX century. Examples of arches have been derived from Western Europe, Middle East and Asia; there are also examples of arches in Polish architecture, not well known in the United States.

A selection of modern constructions illustrates actual trends in arch applications in contemporary architecture.

Jerzy Andrzej Starczewski

ŁUKI W ARCHITEKTURZE

(STRESZCZENIE)

Autor przedstawia zasadę łuku jako konstrukcji ściskanej; pracę statyczną łuku ilustruje doświadczeniami przeprowadzonymi na modelach elastoptycznych. W dyskusji na temat kształtów łuków poruszone są zagadnienia optymalizacji.

Studium zawiera historyczny rozwój łuku od czasów sumeryjskich do XX wieku włącznie. Przykłady łuków pochodzą z Europy Zachodniej, Bliskiego Wschodu i Azji; autor podaje także przykłady łuków w architekturze polskiej mało znane w Stanach Zjednoczonych.

W ostatniej części pracy autor omawia wybrane konstrukcje ilustrujące kierunki stosowania łuków we współczesnej architekturze.

ARCOS EN ARQUITECTURA

Por

Jerzy Andrzej Starczewski

(RESUMEN)

La idea del arco como un miembro en compresión es aquí presentada. El comportamiento estático del arco se ilustra a travez de experimentos efectuados con modelos fotoelásticos. La búsqueda de configuraciones optimas para arcos es tambien discutida.

Este estudio incluye el desarrolo histórico del arco desde los tiempos de los Sumerios hasta el siglio XX. Los ejemplos de arcos aquí presentados se han tomado de la Europa Occidental, del Medio Oriente y de Asia. Tambien se presentan ejemplos de arcos utilizados en la Arquitectura de Polonia, los cuales no son muy conocidos en los Estados Unidos.

Una seleccion de construcciones modernas ilustra las tendencias actuales de aplicación de arcos en arquitectura contemporanea.

Jerzy Andrzej Starczewski

OBLOUKY V ARCHITEKTUŘE

(ABSTRAKT)

Autor se zabývá konstrukci oblouků v architektuře. Statický návrh oblouků byl ověřen experimentálně na fotoelastických modelech. Je provede na optimalizace tvarů oblouků.

V předložené práci je dále podán historický vývoj oblouku jako architektonického prvku od času Sumerské říše až do XX. stoleti. Jsou uvedeny přiklady oblouků nejen ze Západni Evropy, Blizkého východu a Asie, ale i méně známé typy z polské architektury, které nejsou dosud známé ve Spojených Státech Amerických.

Provedený výběr modernich konstrukci naznačuje dalši trendy ve využiti oblouků jako architektonických prvků.

DER RUNDBOGEN IN DER ARCHITEKTUR

von Jerzy Andrzej Starczewski

(AUSZUG)

Behandelt wird die Idee des Rundbogens als Druck-Bauteil. Die statische Funktion des Bogens wird durch Experimente an photoelastischen Modellen veranschaulicht. Die Suche nach optimalen Formen von Bögen wird diskutiert.

Die Untersuchung schliesst die historische Entwicklung des Bogens von der Zeit der Sumerer bis zum 20. Jahrhundert ein. Angeführt werden Beispiele von Rundbögen aus Westeuropa, dem Nahen Osten und aus Asien, daneben auch Beispiele aus der Polnischen Architektur, die in den USA weniger bekannt sind.

Eine Auswahl moderner Konstruktionen veranschaulicht gegenwärtige Tendenzen der Anwendung des Bogens in zeitgenössischer Architektur.

АРКИ В АРХИТЕКТУРЕ

Ежи Анджей Старчевский

(КОНСПЕКТ)

Дается понятие арок как элемент сжатия. Статическая работа арок показана по средством фотоэластических моделей.

Поиски оптимальных форм арок обсуждаются. Работа вкючает историческое развитие арок со времени цивилизации Шумеров до XX века. Берутся примеры арок из западной Европы, Среднего Востока и Азии; также имеются примеры арок в Польской архитектуре, которие мало известны в Соедененных Штатах.

Представленны современные конструкции иллюстрирующие настоящие тенденции применяния арок в современной архитектуре.

建築中的拱形構造

必謝 安吉斯大柴斯基

（論文摘要）

本論文首先討論拱形構造為压縮性結構的各種觀念。作者以光彈性物理學的实驗來顯示拱形的靜態機能。本文亦探究如何達成最佳拱形的形態。

本文探討自苏美時代至二十世紀拱形構造的歷史發展過程。文中有関應用在建築上的例子多取自西歐，中東及亞洲；波蘭建築中的拱形例子亦包括在本文中，惟其在美國少為人知。

從本論文中的幾個近代結構物例子可以顯示出拱形構造應用在現代建築中的發展趨勢。