RELEVANCE OF GEOMETRICAL SYSTEMS IN CONTEMPORARY ARCHITECTURE

A THESIS

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By

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CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in the thesis entitled **"Relevance of Geometrical Systems In Contemporary Architecture"** in fulfillment of the requirements for the award of the degree of Doctor of Philosophy submitted in the Department of Architecture and Planning of the Indian Institute of Technology Roorkee, Roorkee is an authentic record of my own work carried out during the period from August 2002 to March 2006 under the supervision of Dr. Najamuddin, Emeritus Professor and Sh. R. K. Jain, Associate Professor.

The thesis has been revised as per the suggestions of the examiners.

The matter presented in this thesis has not been submitted by me for the award of any other degree of this Institute or any other University.

(Sandeep Dua)

This is to certify that the above statement made by the candidate is correct to the best of our knowledge.

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ABSTRACT

Beauty, utility and technical support are the three fundamental parts which when combined cohesively create meaningful architecture. The approach and appreciation towards beauty or aesthetics in part depended upon the ways various civilizations looked at the universe and created their respective world-view. From their understanding of the universe, creation of the world-view and with the available technology, they formulated laws of beauty, quantified them in terms of numerical proportioning systems and through geometrical figures and impregnated them with meaning. Knowledge of geometry and other mathematics was used not only to give form to an enclosure or for the practical purpose of laying out on site with ease and accuracy but represent the intellectual development of a civilization. Every civilization has determined certain fixed geometrical systems devised over passage of time for its use represent its holistic development and impart identity to it which separates it from the rest of the world. However, despite varied socio-cultural and physical conditions, there is a marked underlying similarity found in the geometrical systems being used in architecture in all the civilizations.

Geometry was thus recognized as a powerful organizational tool to fulfill the intangible and tangible aspects of architecture in all the civilizations. It provided a logical and rational approach towards the making of a building imparting in it the specific qualities necessary to the creation.

The ancient mathematical systems of order in architecture which dominated up to renaissance were questioned by Mannerists and Baroque architects. The concept of universe underwent drastic change and was revealed by science as completely abstract and mathematical, devoid of any harmonic

relationship to the world of senses. The sixteenth and seventeenth centuries experienced a general shift from static to dynamic concepts; from the limited to the infinite continuous space. The abandonment of rules of proportion coincided to some extent and even preceded the development of new cosmology. Michelangelo asserted that all arithmetic and rules of proportion are useless without the observing eye. The Baroque architects and Neo-classicists relied heavily on the eye of the perceiver as the only basis of proportion. Beauty believed to lie strongly in the eye of beholder. Architectural proportions were regarded as the creations of the human mind and not the quality of the thing in itself.

In the nineteenth century, many researchers, through their research and analysis on the creations of nature, attempted to re-establish the supremacy of the proportions used earlier by holding them responsible for the cause of beauty. The major proponents of twentieth century modernism continued this trend by extending their contribution through research and application of these geometrical systems in their buildings thereby reaffirming the traditional role of geometry as an organizational tool in architecture.

This research analyzes these geometrical systems, their application in buildings selected from diverse time-periods in history and from varied cultures, and attempts at establishing the relevance of geometry in contemporary scenario providing a strong scientific base for the application of these systems in architecture.

It began with detailed literature survey analyzing the evolution, significance and application of geometry in architecture through different ages till twentieth century. From the analysis of history different types of geometrical systems namely mathematical proportions, golden proportions, geometrical proportions, regulating lines, module-based proportions, and preferred dimensions were found to be incorporated in buildings. These systems have been described in detail elaborating their specific properties which made them so relevant in architecture.

Significance of geometry as an organizational tool in architecture has been discussed by describing its relationship with various elements like symbolic and visual references, form, space, circulation, articulation, and structure which cohesively contribute in the making of architecture. This information formed the basis over which model was developed for each of the geometrical systems for appraisal of existing buildings or programming of proposed ones.

Buildings from diverse time periods and from wide range of geographical locations, in which these geometrical systems were found to be employed, have been documented and analyzed in order to come out with underlying significant parameters for each of the systems culminating in the formation of model. Nearly half of the buildings belong to twentieth century in order to analyze the application of geometry in recent past and its relevance in contemporary times. The model has been applied on few buildings to determine its best suitability.

Major findings have been elaborated in the form of conclusions determining the relevance of geometry in terms of its importance in imparting order in architecture, its relation with creativity in generating valuable novelty, its role in defining architecture as an independent organism etc. followed by the conclusions based on statistical results.

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Sandeep Dua

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CHAPTER 1

THE RESEARCH CONTEXT

ABSTRACT

Geometrical systems are used for aesthetical, functional and engineering purposes, which means to create overall order in architecture. All great architects in the past were mathematicians. One way to seek GOD was through aesthetic perfection, which was achieved through the application of geometrical systems. All civilizations ascribed their own mystic significance to geometry. The best examples of the use of geometrical systems can be witnessed in the buildings of symbolic and functional value of any period. Research has shown that despite varied socio-cultural and physical conditions, there is a marked similarity in the geometrical systems being used in architecture thereby maintaining the stand of these systems being neutral and simultaneously personal.

This research analyzes these geometrical systems, their application in buildings of different use selected from diverse time periods of history, from different geographical conditions and tries to identify and relate those parameters that significantly affect the respective systems which in turn are responsible for creating holistically meaningful architecture

1.0. INTRODUCTION

Geometry is not only useful to create law and order on earth (as discussed by Calter (1998) [7], originally *Geo+metry* means earth measure, used to restore boundaries of land after annual flooding of river Nile in ancient Egypt), it is also recognized as a paradigm of certainty and truth. It is the powerful tool for the inculcation of clear, logical thinking and reasoning.

Geometry formed the common language of Man for all practical and intellectual arts. The objective of all traditional learning was the development of human intellectual powers for the purpose of self evolution beyond his biological determinism. The practice of geometry was an essential technique towards this end harmonizing matter and spirit. It is derived from an attitude of acceptance from Nature and associated with an attitude to control the human activity.

Geometry as a science is closely related with architecture. Different geometrical shapes and proportioning systems evolved out of geometrical principles determine the interrelationship among different parts of architectural composition thus creating overall order in design. Geometry creates flexibility and widens the choice of organization by varied arrangements of parts on one hand and makes bold statements by pure forms strategically located.

Geometrical systems thus necessarily add essential regularity which is a technical necessity to generate positive emotional responses at different scales within and outside the building. Geometrical shapes and proportions simplify the complex world around us in order to understand and identify the environment.

1.0.1. Historical Background

"Let the one destitute of geometry not enter my doors"

Plato (427-347 BC)
Calter (1998) [7]

Until the seventeenth century geometry was used for the fulfillment of practical and psychological requirements of human beings. It was the basis of architectural design and construction throughout history. Apart from the application of geometry as an organizational tool, its application in architecture represented the intellectual development of a civilization.

From Neolithic period onwards to Renaissance times, the aesthetic principles were based on certain geometrical principles. These geometrical systems applied in architecture were supposedly existing in the very nature of the universe and were considered to be instrumental in the inherent harmony of the cosmos of which human being was an inseparable part. By the application of these systems in architecture, man participated in the harmony of the cosmos. While the main geometrical systems were applied to determine overall order in architecture, human proportions were used for short measurements in the civilizations till the advent of the metric system.

According to Padovan (2001) [48], ancient geometrical systems were declined in Mannerist and Baroque architecture. This was followed by the inventions in science where universe was defined as purely abstract and intangible, known only through mathematical equations having no connection with the sensory experience.

Michelangelo stated that all rules of proportion and arithmetic used in art and architecture are useless without the observing eye. The Baroque architects and the Neo-classicists started relying heavily on the eye of the observer, allied to experience as the only basis of proportion. This view point was reinforced by many researchers at different places in due course of time. The new philosophy replaced the objective and universal standards of art and architecture with the subjective and personal ones. Architectural proportions were regarded as the creation of human mind and not the quality of the concerned object. This tendency had strong influence until late nineteenth and early twentieth century.

Le-Corbusier, the major proponent of modernism after analyzing the historical examples, tried to re-establish earlier geometrical systems through their application in his buildings. He also devised his own proportioning system based on the already known concepts of geometry to fulfill the contemporary demands. The application of these geometrical systems by other prominent architects of twentieth century viz. Louis Sullivan, Edwin Lutyens, F.L. Wright, Mies Vander Rohe, Louis I. Kahn etc, as revealed by many researches, reaffirmed their supremacy. Contemporary architects challenging the age-old concepts of design and exploring new boundaries of architecture more compatible for the cyber age, however, rely faithfully on these concepts. The prime concern of this investigation is to see the relevance, significance and application of these geometrical systems in contemporary scenario.

The "Geometrical Systems" here include the varied proportions, regular geometrical shapes, regulating lines and preferred dimensions (the modular), which have been utilized to impart the quality of 'order' in architecture.

1.1. RESEARCH DESIGN AND METHODS

Though geometry has its contribution in all respects for the creation of meaningful architectural form, however, the research in this area is limited only in the relationship of geometry to the metaphysical and aesthetical factors thereby undermining the full potential of geometry as a strong organizational tool in architecture inherently related to all other tangible aspects which jointly contribute in the making of desirable built form.

1.1.1. Hypotheses

The following hypotheses are framed based on the analysis of literature

(i) The application of geometrical systems provides rational approach towards the creation of holistic architecture.

(ii) The great architecture of the past across different cultural boundaries and time dwells on the systematic application of well-defined geometrical systems.

(iii) Geometrical systems are very much relevant in creating meaningful architectural forms in contemporary scenario.

(iv) There is a need to establish a rational basis for the application of geometrical systems in architectural design for ensuring contextually and functionally appropriate, and aesthetically pleasing architecture.

1.1.2. Objectives

The chief concern of this research is to put forth the relationship of the geometrical systems, being applied in architecture and their major aspects that contribute collectively in the making of a meaningful form. This would also include identification and the system of application of those parameters that significantly affect the respective systems. A set of objectives have been framed to accomplish this task.

i) To seek the evolution, application and significance of geometrical systems used in architecture through the ages in varied cultures.

ii) To investigate in detail varied geometrical systems applied in the formulation of architectural form.

iii) To examine the role of geometry as an organizational tool in architecture by analyzing its relationship with different elements which cohesively contribute in the concretization of architectural form.

iv) To come out with a systemic approach for the application of these geometrical systems in contemporary architecture.

v) To evolve a set of conclusions necessary for the use of geometry in architecture.

1.1.3. Scope of Work

Since most of the designers in the past were basically mathematicians, the discipline of geometry enjoyed a special status in the making of holistic architecture. However, in seventeenth century, the age-old application of geometrical systems was questioned whose impact persisted for a long period and can be felt to some extent till date. Keeping this thing in mind, the research work proceeds in the following direction:

i) It would identify the different geometrical systems used in architecture which resulted in vast variety of form.

ii) It would analyze the relationship of geometry from all the aspects that contribute in the making of architectural form.

iii) It would investigate how the relevant geometrical systems have been applied meaningfully in architecture thereby seeking facts which go beyond the realm of architectural styles within which architecture is generally categorized.

iv) If would find ways how the relevant geometrical systems are applicable in architecture right from the beginning of the design stage.

v) The study will record and analyze relevant research work done in this area by various researchers in a systemic way to meet the set objectives.

1.1.4. Methodology

The relevance and significance of geometry was established by various researchers in different periods since the dawn of the civilization. Varied geometrical systems were developed, used and interpreted according to the particular world-view prevalent in respective periods. The role of geometry as an organizational tool in architecture was always recognized in all the periods. However, this age old notion was challenged in the seventeenth century and its influence sustained for more than two hundred years. Isolated attempts were made in the twentieth century to restore the previous significance attached to the role of geometry in architecture.

In order to establish a scientific basis for the application of geometrical systems in architecture right from the design idea stage, this research work was taken up. This investigation consists of the following steps:

(i) Study of available literature regarding the application and significance of geometry in architecture through ages and in different cultures.

(ii) Identification of prominent geometrical systems used in architecture

(iii) Analysis of importance of geometry by studying its relationship with architectural elements like form, space, circulation, structure, etc.

(iv) Determination of control parameters that collectively generate architectural form.

(v) Identification of buildings from available literature to analyze the relationship of geometry with different architectural elements.

(vi) Preparation of 'Data Base' by identifying the use of different geometrical systems along with the presence of relevant control parameters in each of the selected buildings.

(vii) Identification of significant control parameters in relation to each of the geometrical systems.

(viii) Application of suitable statistical model on the above created 'Data Base' which would relate the occurrence of significant control parameters against the use of each of the geometrical systems in existing as well as proposed buildings.

(ix) Determination of role of geometry in architecture through the analysis of relevant literature.

(x) Employment of model for best applications in selected examples.

(xi) Framing integrated conclusions regarding the application of geometry in architecture based on analysis of literature and the derived model.

This methodology has been summarized in the form of flow chart in Appendix –I.

1.1.5. Data Collection and Softwares Used

Data has been collected mainly from secondary sources. The study depends heavily upon this data for analyzing the role of geometry in architecture over the passage of time in varied cultures spread over different parts of the world in order to extract the underlying commonalities in its applications resulting in the production of built forms so diverse in nature. The literature has been collected from the sources such as books, dissertations, journals, monographs and from various websites through internet.

Three softwares were used for the accomplishment of this work- AUTOCAD and Adobe Photoshop for drafting and editing purpose of drawings and visuals to make them easily comprehensible.

Statistical software like SPSS was utilized for analytical work like selection of significant control parameters and working with model to arrive at relevant observations and conclusions.

1.1.6. Analytical Procedure

The present study is theoretical in nature. To understand the application of various geometrical systems in the making of architecture, through pre-historic to contemporary times, forty buildings have been selected for analysis. The examples chosen belong to different places, functions, periods and styles, which contributed visibly significant developments in architectural form. The intention is to explore the commonality of those design ideas where these geometrical systems have been incorporated in generating architectural form.

1.1.6.1. Selection Criteria of Buildings

Out of the forty buildings analyzed, majority of them (twenty-two in number) belong to 20th century. These are the seminal works by different architects exerting strong influence on the basis of their varied philosophical and innovative approach towards design. Their influence is witnessed on the direction of contemporary world architecture. The realm of analysis is concentrated only on the single works of architecture exploring the formal, spatial and structural aspects of built form. The selection of buildings was also limited by the availability of the relevant information.

Though many persons contribute in the designing and making of buildings, here in our work we associate the building to the person who is mainly recognized as the designer in the available literature. Normally not more than one building of one designer is chosen for analysis, except Le-Corbusier, whose seven buildings have been analyzed to understand his geometrical system, the modular, and its applications in his buildings.

First of all, the six types of geometrical systems which were found to be applied in the making of architectural form, called dependent variables in statistical terminology, were listed. Different elements that contribute to the creation of architectural form like space, circulation, structure etc were also put forth. Under each element, detailed control parameters called independent variables were placed.

Dichotomous data in respect of both dependent and independent variables in the form of '0' and '1' was generated, where '0' represents the absence of any particular variable while '1' refers to its presence against each of the forty buildings. An attempt was thus made to present information qualitative in nature into quantitative dichotomous form.

The data thus generated was analyzed with optimal statistical tools and techniques such as Gamma Coefficient of Association for Ordinal Variables for the determination of significant control parameters in respect of each system followed by the application of Logistic Regression with which model was generated for each geometrical system separately. The evaluation approach consists of two dimensional matrix where one side expresses the application of geometrical systems white the other represents the presence or absence of control parameters.

1.1.7. Limitations

(i) This investigation is concentrated on the application of geometry in the creation of architectural form as a product universal in nature independent of regional factors thus laying a broad base over which further research can be carried out integrating the vast physical and psychological aspects thereby adding richness and variety so essential in architecture.

(ii) This work falls in the realm of applied research where the geometrical analysis of architectural form of the existing buildings had been done by other researchers earlier. The investigation done here is a further step, which is based on that already existing analytical work.

(iii) Since the intention here is to form a broad base, which would be applicable universally, the analysis here is restricted to the individual works of architecture without considering their response to their respective urban settings.

(iv) In order to identify the most common base applicable to different kinds of buildings, this study does not include the cost factor, the furniture arrangement, and the services part of buildings where these geometrical systems have been applied.

(v) The investigation includes buildings of religious, symbolic, cultural or ritualistic importance and other structures like educational, financial and administrative institutions, housing and single residences, convention centres where architecture is a result of balanced approach to different elements like symbolic and visual references, form, space, circulation, articulation, structure, etc.

1.1.8. Concluding Remarks

This research is an attempt to quantify and relate the effective qualitative as well as quantitative parameters of architecture in the form of a model, which can be considered for analyzing existing buildings and for making decisions for proposed ones thereby providing a strong scientific base for the application of these geometrical systems in architecture.

1.1.9. Organization of the Work

The investigation consists of eight chapters submitted to various aspects of geometry in architecture. A brief description of each is given below:

Chapter one deals with introduction of the subject spelling out the objectives, methodology, scope and analytical approach to achieve the set objectives followed by concluding remarks. It thus forms the comprehensive view about the way the overall research work has been carried out.

Chapter two discusses the application of geometry in architecture in the historical context. It reveals the relevance of geometry in the making of architectural form in different periods and in varied cultures finally arriving at its status in contemporary situation.

Chapter three unfolds the diverse geometrical systems being used in architecture over the passage of time expounding upon the special properties of each of them.

Chapter four explains the significance of geometry as an organizational tool in architecture. It determines the relationship of geometry with all the varied elements of architecture and is a central source in the formation of the further analysis carried out in this research work.

Chapter five discusses the identified case-studies where geometrical systems have been found to be incorporated in their making.

Determination of detailed control parameters, data preparation evaluating the selected case-studies finally arriving at separate models for each of the identified geometrical systems constitute the main contents of chapter six.

Application of model is carried out on few selected buildings in chapter seven, to check its applicability and appropriateness.

Chapter eight presents in a synthesized form a series of conclusions based on the analysis of literature, data collected from the case studies and statistical model.

CHAPTER 2

APPLICATION OF GEOMETRY THROUGH ARCHITECTURAL HISTORY

2.0. INTRODUCTION

From Pre-historic time onwards, after fulfilling the basic needs of life man tried to understand his surrounding environment. He observed the natural phenomena and started associating meaning to it. The meaning shared collectively by the community started finding its representation in the built form. This symbolism was based on the intellectual development of the community. The intellectual developments here include religious and scientific ones. The architecture of the community which used to represent their culture used highest level of technology available to them to represent their symbolic values.

The first scientific developments, as considered, took place in the field of astronomy. The interest in astronomy was developed by observing the daily movements of sun and moon, the cyclic changes of season, and occurrence of other astronomical events. The attempt at accurate determination of these astronomical events gave birth to the first use of mathematics. Through out the course of history so it is observed that the buildings which represent the development of a civilization are mainly the buildings of symbolic value and of scientific developments. The symbolic architecture means the architecture of religion, culture and power e.g. temples, mortuary places, palaces etc whereas the scientific architecture includes wind towers, observatories, large span exhibition buildings and warehouses etc. and in some cases the two kinds were combined very strongly to give the feeling of awe e.g. stonehenges of England, pyramids of Egypt, temples of Rome etc. These two types of buildings used geometry but for different purposes, whereas the buildings having high symbolic value used geometry that was infused with mystic meanings, the architecture showing scientific and technological developments used mathematics to show and experiment the newest possibilities that shape the environment and represent the triumph of man. Whereas the earlier type falls in the realm of feeling, the second one occurs in the realm of thinking as Giedion (1956) [32] puts it.

The architecture of the past is appreciated because it maintained the balance between thinking and feeling. In other words, it can be said that master pieces of architecture were created with the balanced and integrated use of mathematics to fulfill the psycho-physical needs of man.

As mentioned, the understanding of the universe was the source of symbolic and scientific developments of any civilization; it has been observed that the major geometrical proportions used in architecture from the earliest times were proportions that supposedly existed in the very nature of the universe and by using these proportions man participated in the harmony of the cosmos. It was only the Greeks who in their grand enquiry of the universe made these relations apparent. Through their deep, systematic and rational enquiry of the universe, they established their facts systematically and convincingly. Research shows that these very proportions were used effectively in the pre-classical art and architecture though not much authentic records are available as in the case of classical times onwards.

About 500,000 years ago human being started observing the passage of time so as to adjust himself according to the seasonal variations. About 30,000 to 27,000 years ago, man started keeping accurate track of time by recording the changing phases of moon and putting them in the form of calendars. The initial speed of development was slow, took a long time between observing the passage of time and recording it accurately." What we realize that keeping track of time - recording history is an intrinsically human activity" (Crouch, 1985) [14]. Further developments however became faster. It took only 20,000 years for man to create built environment suitable to his specific needs from cave dwellings to permanent stone structures. About 10,000 years ago, permanent settlements in stone structure were available such as the wall of Jericho. "In a mere 6000 years more, or 5000 $\pm$ 300 years ago, there was a knowledge explosion - the invention of writing and numbers – and cities cropped up along major rivers all over the eastern hemisphere-in Africa, the Middle cast, the Indian continent" (Crouch, 1985) [14]. The course of developments in architecture involved a lot of experimentation with different kinds of materials available nearby combined with higher level of intellectual development yielding sophisticated artifacts.

This is evident in the artificial mountains of high symbolic value built in the flat plains between the Tigris and Euphrates rivers in the mid of 4th millennium BC, known as Ziggurats of Mesopotamia, built up of millions of sun-dried bricks. A permanent structure of high quality built of impermanent material was produced.

Though stone construction existed earlier but third millennium BC saw the bold experiments in stone for more permanence and better control over the shape and size of the material for specific purpose. The examples of such stone construction are the simplest dolmen tomb of Brittany and the channel islands of 4500 BC, the complex temples of Malta of 3000BC, and the stone circles (stone-henges) of the period 2500 – 1700 BC.

2.1. NEOLITHIC ARCHITECTURE

Starting from Pre-classical times, the Neolithic architecture stone constructions from Malta to Ireland consisted of Menhirs (standing stones), dolmens (roofed structures), and stone circles. The best known of these were the stone circles known as stonehenges (stone circles with ditches) constructed in Britain and Ireland from 2500-1700 BC approximately. Different authors have attached different importance to the stonehenge. "The astronomer Gerald S. Hawkins... believes that Station-stone rectangle was immensely significant ... historically, geometrically, ritualistically and astronomically" (Doczi,1994) [17]. Strover, an anthropologist, and Kraig, a pre-historian, also see stonehenge as a monument of funerary centre according to Crouch (1985) [14].

Crouch (1985) [14], also mentions that the space enclosed by the stones, their height, location and number, the specific placements of Heel stone, the Slaughter stones, the Station-stones, the Bluestone trilithons in Sarsen circle were predetermined accordingly to keep the track of time and to mark the movements of astronomical bodies accurately. He also mentions very strongly that the number of different stones used in the stonehenge were fixed according to the positions and movements of the sun and the moon. The placement and size of stones also share mathematical relations. "It seems to have escaped notice so far that the architecture of Stonehenge shares the proportions of the golden section and of the Pythagorean triangle. The classical construction of the golden section applied to plan of Stonehenge reveals that a golden relationship exists between the width of the Bluestone Trilithon Horseshoe and the diameter of the Sarsen circle (1:0.618 = 1:1.618...) ...Geometric analysis with the help of centerlines of piers and diagonals also shows that the proportions of the Sarsen archways come as close to the relationship of 3-4-5 triangle" (Doczi, 1994) [17]. So musical harmonies like diatessaron (3:4), diapente (golden section) and diapason seem to have existed before Greek period. The above mentioned researchers have considered the shape of the stonehenge as circular one but as mentioned by Stevens (1990) [60], the stonehenge were not of circular shape but either oval or egg shaped which has also been questioned. Various arguments have also been presented over this matter.

He puts forward the idea that these stone rings were originally intended to be circles only but such odd forms could be the result of laying out these rings simply by eye only without the use of any geometrical tool. Circles thus can be considered as a link between, astronomy, mathematics and architecture. The stonehenges built between 20th to 16th centuries BC in the Salisbury plain in England are very famous.

2.2. EGYPTIAN ARCHITECTURE

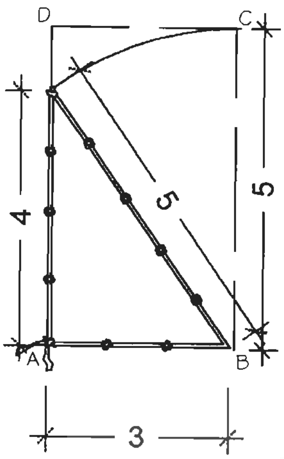
Egyptian architecture dates back to 3000 BC some 1000 years before the stone constructions mentioned above. Egypt, in general, is a desert area having simple and regular geographical character with river Nile as a strong natural feature flowing north-south. The main architectural tasks were pyramids and mortuary temples. It has been claimed by many authors that pyramids were royal tombs to preserve the body of the king after death and the pyramids were used by priests for astronomical and astrological purposes, but recently in an article of 2003" Great Pyramids Facts and Statistics" the author in the context of pyramid of Giza built in 2650 BC says that this pyramid was built as a place of defense and armament in the mythological war among deities. So pyramids had a strong mythological and scientific significance. It is also believed that the glowing-casing stones of pyramid were probably used to help navigators of Nile at night. "The whole symbolism rests on the accepted correspondence of things, on an intuitively conserved and perceived connection between the microcosm and macrocosm" (Norbergschulz, 1975) [47]. After the seasonal flooding of river Nile, geometry was used to re-establish the boundaries of land on either side by dividing it in orthogonal co-coordinating system with river Nile acting as a longitudinal axis thereby restoring law and order on earth.

The other strong characteristic of Egyptian architecture is the unification of horizontal and vertical to form orthogonal space. "Axiality and orthogonality represented the physical and mythological order" (Norbergschulz, 1975) [47]. The pyramids of Giza were the first full fledged examples manifesting true synthesis of horizontality and verticality. This pyramid complex has three similar pyramids in the same orientation each with its axially laid out mortuary temple and long causeway leading down to valley temple on the river. The temple is axially laid out symbolic arrangement oriented towards east. The spaces gradually become smaller as one penetrates deep towards the sanctuary. The sanctuary is an enclosed cell with false door in the west wall which culminates the longitudinal axis.

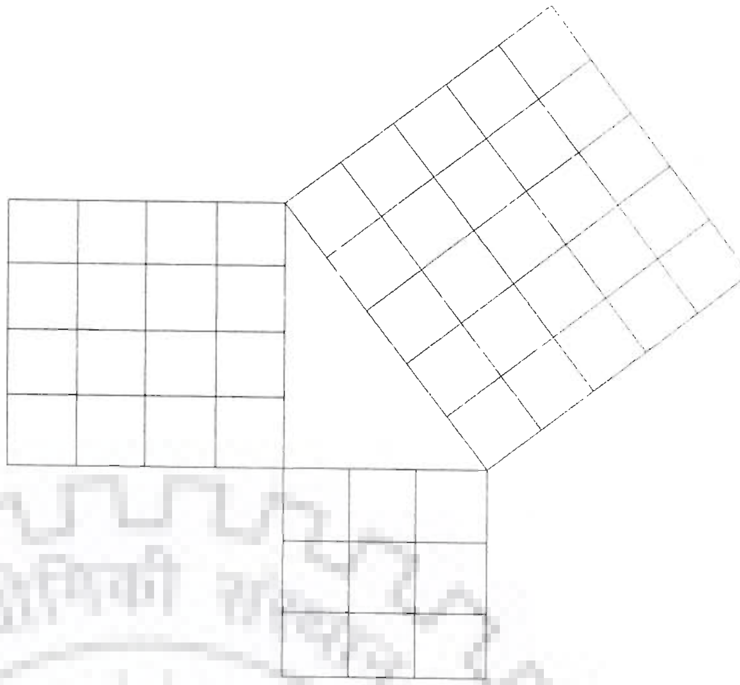
The prominent mathematical relations evident in Egyptian architecture were the use of golden number Phi (ϕ= 1.618...), Pi (π = 3.14...), 3-4-5 triangle (rope stretcher's triangle made up of 12 sections with eleven equidistant knots. At the third and eight knot the rope was fixed and the triangle was formed by joining the two ends) used as a surveying tool later known as Pythagorean triangle. Human proportions were used for short measurements. The unit of measurement was cubit 'length of man's forearm with hand outstretched' (Doczi, 1994) [17] equals to six handbreadths or palms. Each palm or handbreadth equals 3 inches. Royal cubit consists of seven palms and 'fist' equals one and a third handbreadth used only for royal statuary. Slope was measured in *seked.* Seked is the horizontal distance traversed for each royal cubit of vertical distance. It was expressed in palms. Stevens (1990) [60], mentions that almost all pyramids had a seked of 5 ½ or 5 ¼ . He further states that Egyptians invented reciprocals (symbolized by 1/n) but did not make a generalized reasonable notation in terms of fractions to handle them. Different researchers have given different view-points about the knowledge of geometry to Egyptians.

"...they were not good at elementary geometry shows that the pyramids, great an accomplishment though they were, did not require very sophisticated mathematical skills." (Stevens, 1990) [60].

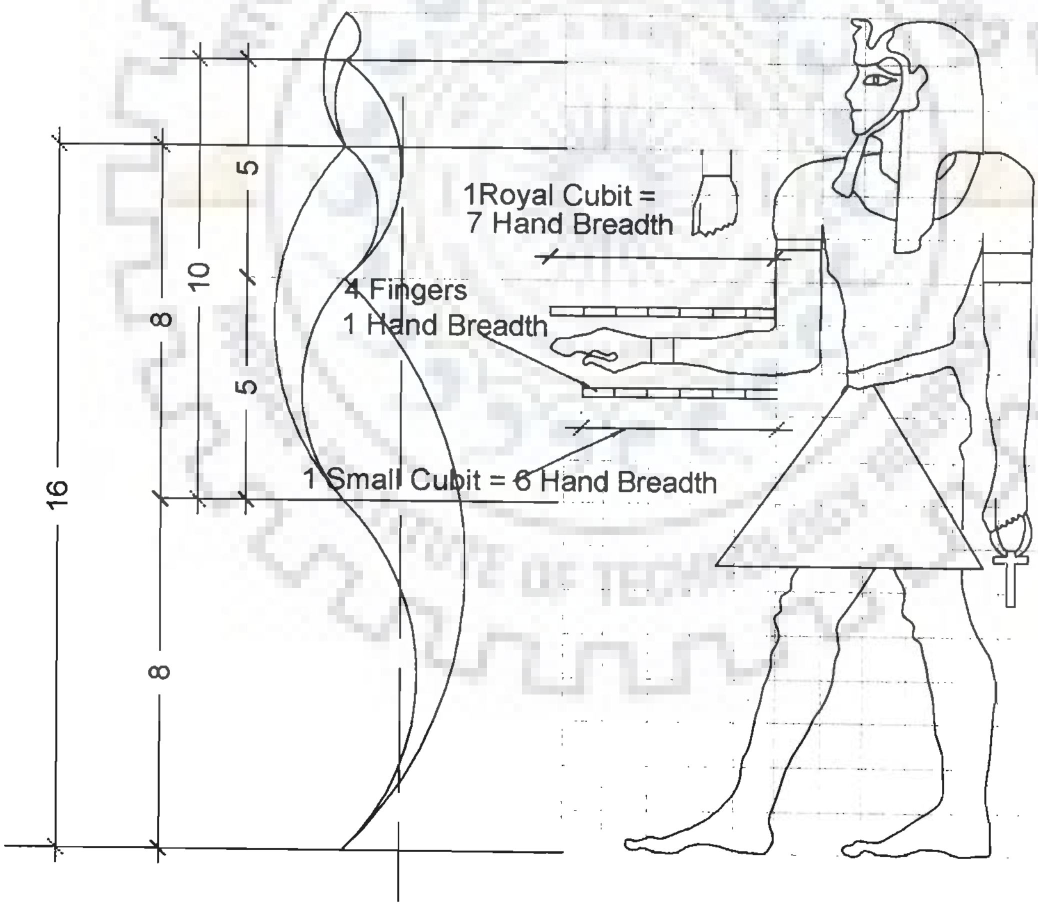
Paul Calter (1998)[7], ascribes symbolic meanings to above mentioned mathematical relations used by Egyptians and states the astronomical



Rope Stretcher's Diagram



3-4-5 Pythagorean Triangle



Egyptian Measures and Proportions Each Square Grid is of Fist

Fig 2.1 EGYPTIAN MEASURES AND PROPORTIONS

importance of the pyramids. Peter Brinkworth and Paul Scott proved that the Egyptians knew the method of finding out the volume of truncated pyramid.

The recent article 'Great Pyramid Facts and Statistics' (2003) goes much ahead and describes that the pyramid of Giza has been thoroughly measured with the details of all the lengths of sides, faces, areas, angles between different sides and edges. The exact number of stones, their weight, sizes, dimensions of casing-stones etc is also measured. This paper affirms concretely the geophysical and astronomical relations of these pyramids through mathematical interpretations. "The three major Egyptian pyramids of Giza are aligned to the three stars in Orion's belt. The alignment is in accordance with Dwat, the art of placement as it is practiced in ancient Egypt, wherein the structures of the earth are positioned to mirror the architecture of heaven".

This article also states that these pyramids are located in the centre of the land mass of the earth, accurately aligned facing true north. Also the curvature in the faces of the pyramid is similar to the faces of the earth etc.

Number of researchers have confirmed that golden section relationship exists between the apothem (356 cubits) and half the base (220 cubits) in this case of Great Pyramid of Cheops apart from the calendrical and other importance associated with this structure.

Matila Ghyka (1977) [31], discusses the discovery of Prof. Moessel (a Munich architect). Ghyka writes that Prof. Moessel discovered the use of golden section relationship in the important monuments of every great period for flexibility and variety of proportional interrelationships. Prof. Moessel inscribed the plans, elevations or sections in a circle or several concentric circles of one or more regular polygons. The controlling circles were divided into 4, 8 or 16 equal parts or more frequently 5 or 10 or 20 parts, in which case golden section relationships are automatically introduced. Ghyka reproduced the analysis done by Prof. Moessel over the Egyptian temple. Rock Tomb at Mira explains his concept lucidly.

2.3. GREEK ARCHITECTURE

Though the ratios which were considered to be the source of harmony of the universe were known prior to the Greeks, it were the Greeks who in their grand enquiry of the universe started looking for rational justification of the nature of things in universe.

"At the heart of the grand enquiry is the commitment to the answering of questions by rational argument and evidence, as distinct from settling them by custom, authority, revelation or rule of thumb"(Stevens, 1990) [60]. The whole universe was explained as unified, interdependent and mathematical in nature. The harmonious musical notes were known before the Greeks, but it was Pythagoras who interpreted them mathematically. The harmony in music was found to lie in the ratios of 1:2 (octave/diapason) 2:3 (fifth/diapente), 3:4 (fourth/diatesseron), 1:4 (double octave). The whole harmonic system known to Greeks appeared to lie in the ratios of 1:2:3:4. "The first four numbers regarded by the Pythagoreans as constituting a spatial hierarchy: 1 corresponded to the point, 2 to the line, 3 to the plane and 4 to the solid" (Padovan, 2001) [48].

Pythagoras taught that while moving around earth, which was considered as the centre of the universe, each of the seven planets along its orbit produced a tone corresponding to its distance from earth. These were the same notes as are found in the musical ratios. Pythagoras named this the 'music of the spheres'. Plato described that all the interdependent harmonics within the universe depend upon the interrelationship of these numbers. These numbers were charged with mystical significance. They were represented with their squares and cubes in the form of greek letter lambda.

1
2 3
4 9
8 27

The whole universe according to Plato consists of separate elements. In his theory of proportion he introduced that the function of proportion is to bind things together to construct an integrated whole from these separate elements. Two extremes are connected by a third element called mean. The discovery of numerical ratios goes beyond music extending towards the whole of space.

"Timaeus was the first to distinguish between harmonic, arithmetic and geometric progressions" (Calter, 1998) [7].

In his book 'Timaeus', Plato described that the universe in created in geometric progression. The proportions of these progressions determine the proportions of musical scale. Minimum three numbers are required to make a proportion. Plato mentioned that the sensible world is the reflection or representation of the Universal or True Form and the ultimate truth lives in this True Form. Mathematics was given the divine status by Plato and was considered to be the pre-requisite to understand the world and the ultimate truth. Padovan (2001) [48], in his book 'Proportions' argues with the reference of other earlier authors that in order to make the universe intelligible for himself, man constructed it in the image of his dwelling using the same geometrical shapes of circle and square with which he built his house. These shapes, he claims, are otherwise not commonly visible in nature except the sun & the moon.

The mathematics known to Pythagoreans consisted of numerals, which mean the simple integers and rational numbers. The discovery of irrational numbers found its representation in geometry as Wittkower (1953) [83] mentions it.

Both Rudolf Wittkower and Jay Hambidge believed that two kinds of proportions existed in Greek architecture. Whereas Wittkower identifies them as arithmetical / numerical/commensurable (1 : 2 : 3 : 4) and geometrical / incommensurable proportions $((\sqrt{2}, \sqrt{3}, \sqrt{5}, \phi, \phi^2, \sqrt{\phi})$. Hambidge (1924) [24], calls them as static and dynamic symmetries respectively. Hambidge further lays stress over the superiority of dynamic symmetry like that of the golden section, he characterizes dynamic symmetry as the basis of living organism and so having highest artistic value. He claims the extensive use of golden section and $\sqrt{5}$ as the basic dynamic proportion used in Parthenon from the all-major dimensions to the minute details. However his theory has also raised many doubts as Padovan mentions by giving references of many other researchers who do not agree with Hambidge.

The 3-4-5 triangle, the isosceles triangle, the pentagon and pentagram were infused with mystical significance. Later on Plato ascribed the five solids known as Platonic solids - tetrahedron, octahedron, icosahedron cube, dodecahedron; the only five solids having equal faces, equal angles, equal sides - special significance by relating four of them to the elements that compose the universe. The four elements fire, air, water and earth are related to each other in the same ratio through geometrical progression, so that:

" Fire/air = air/water = water/earth

This ratio is constant between successive elements, giving a geometrical progression. The Platonic solids belong to the group of geometric figures called polyhedra "(Calter, 1998) [7]. The fifth one-dodecahedron later on was ascribed to heaven or ether.

Temples and theaters were the most important building tasks. The other activities include the stoa, the dwelling etc. Whereas the individual greek building is governed by the rules of geometry and symmetry, the greek cities were planned on orthogonal grid. Greek temples appear as clearly defined plastic bodies with external colonnade having primary importance. Temple is visualized as muscular body. The plan is axial with orthogonal organization. Classical orders were developed to impart individual character and particular experiential quality. The sacred architecture is distinguished by the presence of pediment which synthesized the horizontal and vertical like the pyramid.

Vitruvius (1960) [44] mentions the use of numeral system in greek architecture. Human body was considered to be the example of perfect harmony and beauty created by the God and so the study and applications of its proportions were necessary for the creation of perfect buildings. Circle and square seemed to circumscribe perfectly the human body. The units of measurement foot, palm, cubit, and the perfect number ten, six and later on sixteen were derived from the basic unit –finger.

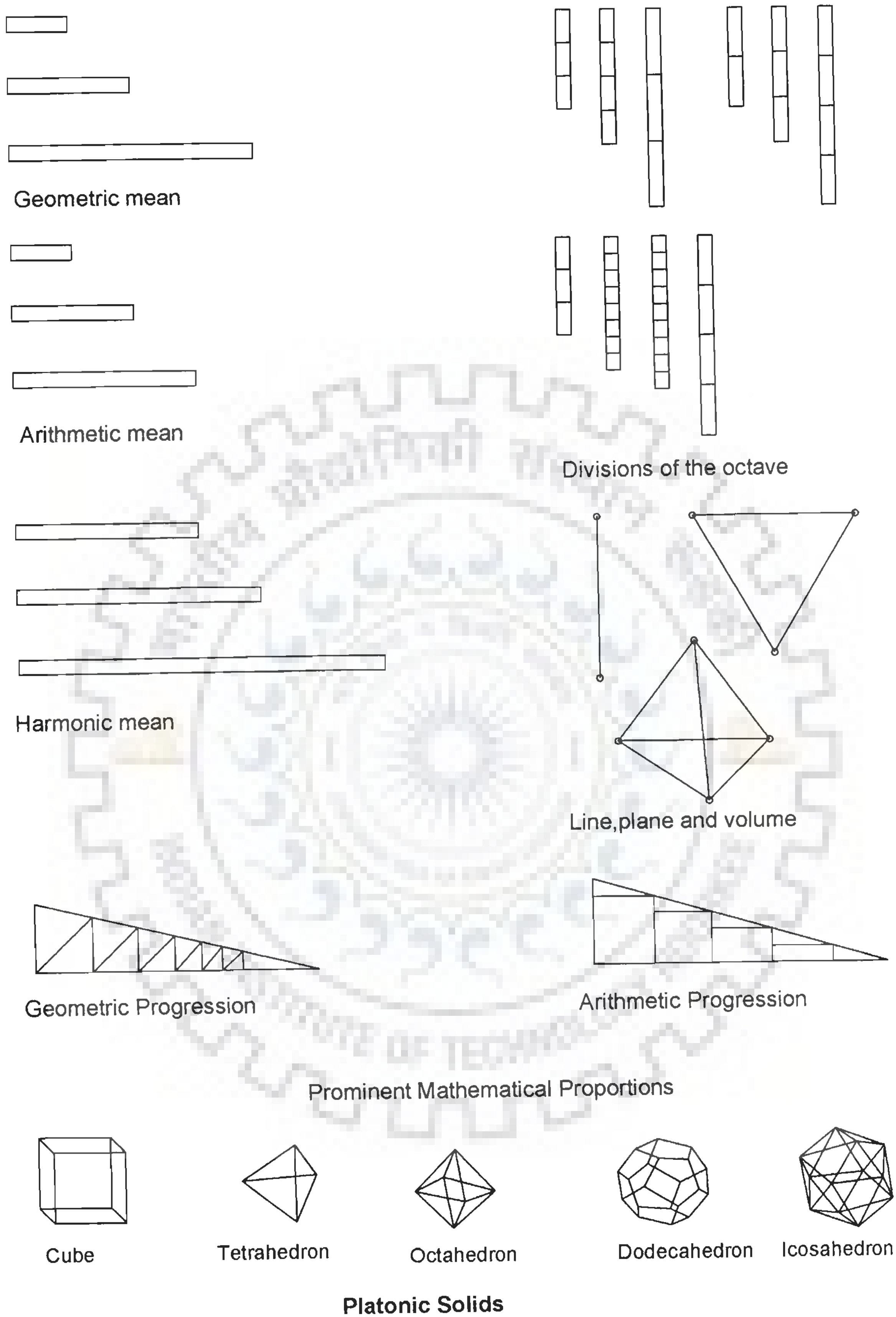


Fig 2.2 GREEK GEOMETRY

"Architecture depends on order...Order gives due measure to the members of a work considered separately, and symmetrical arrangement to the proportions of the whole...By this I mean the selection of the modules from the members of the work itself and, starting from these individual parts of members constructing the whole work to correspond" (Book 1, Vitruvius) (1960) [44].

As found in the books of Vitruvius-Two kinds of proportioning systems were developed by Greeks. The first one is a modular system in which the lower diameter of the column was fixed as a module and all the other dimensions were the multiples of this module just as foot is the basic module and other proportions of human body are expressed in the multiples of foot. The system was followed in the temples with Doric, Ionic and Corinthian orders. The temples with Tuscan order followed relative system of proportioning. The lower thickness of columns was fixed as one-seventh of its height, the height as one third of the width of the temple and so on. So change in one proportion profoundly affects the overall appearance of the temple.

Doczi (1994) [17], analyzed two Greek temples built in two different times. One is the Parthenon at Athens, an example of Doric order, the other one is the Athena Temple at Priene, example of Ionic order. Through his analysis he proves the extensive use of musical ratio 2:3 (fifth), which he almost overlaps with golden ratio ϕ, along with the use of other musical ratios.

2.4. ROMAN ARCHITECTURE

Roman architecture is known for its multitude of building types other than religious ones. It includes basilicas, termae, palaces, triumphal arches amphitheatres, circuses etc. Yet they have common fundamental planning principle. Roman buildings are marked by strict axiality emphasizing centre which is generally marked by the crossing of axes. The Romans manifested their cosmological image at every level by marking two main axes running from north to south and from east to west intersecting each other at right angle, thereby dividing the space into four main parts. This defined space within the boundary of the horizon was called templum. The primary axis running north to south, called *cardo*, represents the axis of the world and the secondary one running from east to west, called, *decumanus*, represents the course of sun. This same orthogonal cosmological order formed the basis of Roman organization at all levels from a single building to that of a city. City was perceived as a microcosm. Spatial configuration and articulation was the prime characteristics in Roman architecture. Stress was laid on interior of the building and the relation of the building with the urban context.

"This image represented a world order abstracted from certain natural phenomena such as cardinal points and from ancient symbolizations such as 'spiritual' vertical, the 'profane' horizontal and the concepts of centre and path" (Norbergschulz, 1975) [47]. The orders impregnated with symbolic meanings during Greeks were reduced to more surface decorative elements in Roman buildings. Roman never strived for the knowledge of timelessness.

Doczi (1994), in his analysis of two Roman structures, 'The Triumphal Arch' of Constantine and 'Colosseum', proves the similarity of proportions used by Greeks as well as Romans. He proves the extensive use of golden ratio ϕ/2:3 (diapente) along with the musical ratios and $\sqrt{5}$ in these structures. . He further mentions the use of golden relationships in terms of number of lines in various parts of narrative corresponding to Fibonacci numbers in Roman poetry.

2.5. THE MIDDLE AGES

The classical principles persisted through the Dark ages in fragmentary form. The two great thinkers St. Augustine (354-430 AD) and Boethius (480-524 AD) incorporated Plato's theory into Christian theology. Pythagoreanism and Plato's mathematical and musical treatises became part of Christian philosophy in the West till the rise of Aristotelianism in the thirteenth century. The science of mathematical proportions in Plato's Timaeus' and Vitruvius' 'Ten Books' of architecture as part of Greek architectural tradition survived through the medieval period. Rules of proportions formed the basis of beauty. Mathematics had a divine status and was considered a link to God. One way to seek the will of God was through aesthetic perfection achieved by the extensive use of mathematics.

Of the two kinds of proportions mentioned in 'Timaeus' the numerical/commensurable ratios associated with musical harmony (1:2:3:4) and the geometrical ones based on geometry of regular solids and incommensurable ratios $(\sqrt{2}, \sqrt{3}, \sqrt{5})$, it was the former that dominated from the fall of Roman empire to the early middle ages. Mathes Roriczer's 'Geometry in German' discussed some geometric rules exemplifying the use of geometrical system of proportioning. Padovan (2001) [48], argues that such firm evidences belong to the end of the Gothic period. Roriczer's book discusses the method of construction of geometric figures like regular pentagon, heptagon, octagon, drawing of square and equilateral triangle of

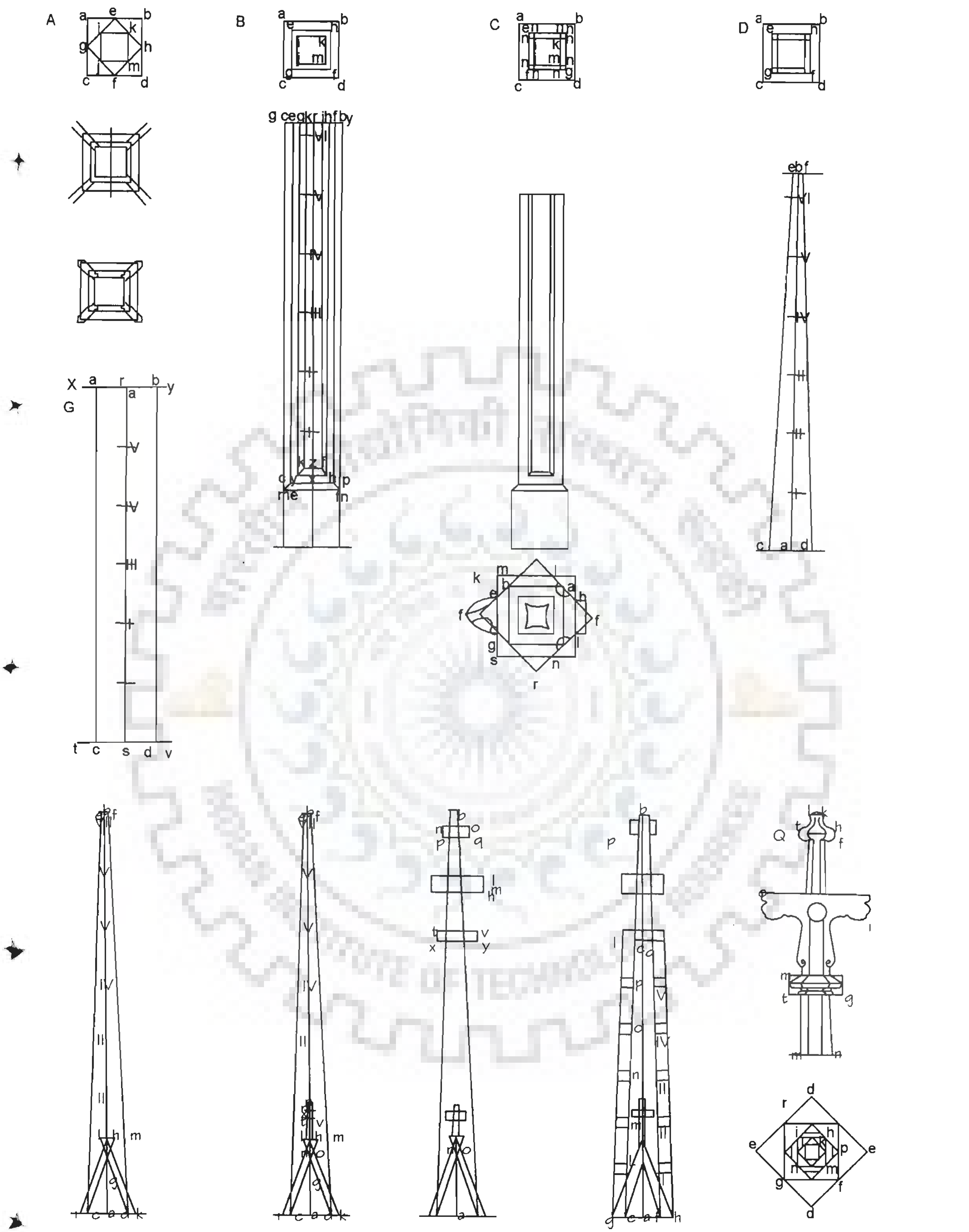


Fig 2.3 (a) RORICZER'S SCHEME FOR DETERMINING THE PROPORTIONS OF A PINNACLE (1486)
Hamlin (1952)

equal area, calculation of circumference of circle etc. These methods are based on experience.

In his book 'On Pinnacles' Roriczer gave 234 meticulous steps of designing a pinnacle. He starts a pinnacle with a square base, inscribes another square joining centers of all four sides of the base square. This square has an area equal to half of the base square, in the second square, he inscribed the third square by joining the center points of second square and so on but he gives no justification.

Another book by Hans Schmuttermeyer 'Book on Pinnacles' still provides another way of making pinnacles by fixing a system of modules. There is no need to know the numerical dimensions of space. Once the basic dimensions of modules were fixed, the other dimensions were multiple of these modules.

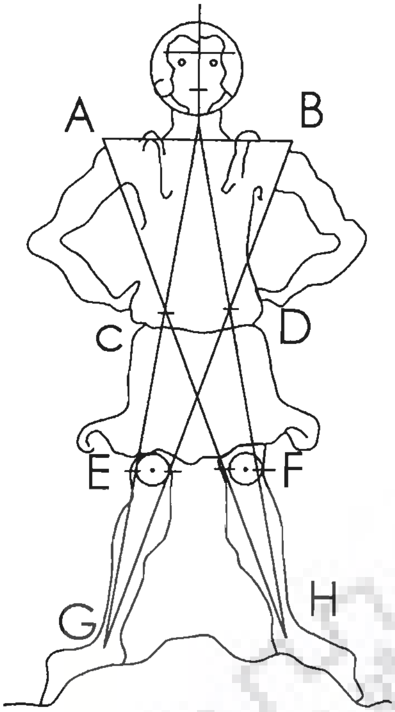
These texts were very helpful since the construction work of most of the religious buildings progressed through many generations and these rules were helpful to maintain continuity among different generations. Gothic architecture was an age of experimentation. In every attempt the artisans strived to do better. This is evident in the excellence they achieved in their development of structural systems. In the period between 1150 and 1280 the wall thickness in cathedrals were reduced from 1800 to 400 mm.

According to Wittkower(1953) [83], "The equilateral triangle, the right angled isosceles triangle, the square and pentagon and derivative figures like octagon and decagon formed the basis of medieval aesthetic... Most medieval churches were built ad-quadratum or ad-triangulum... The medieval quest for ultimate truth behind appearance was perfectly answered by geometrical configurations of a decisively fundamental nature that is by geometrical forms which are irreconcilable with the organic structure of figure and buildings". Padovan (2001) [48] mentions that Roriczer does not discuss specifically about 'ad-triangulum' based on $\sqrt{3}$ proportion in his books and his works provide very few clues regarding the proportioning system in gothic architecture.

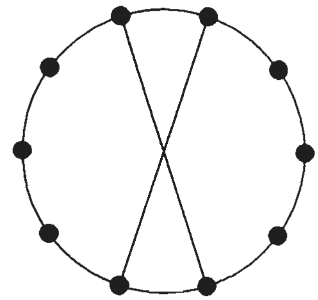
The methods of the 'ad-triangulum' and 'ad-quadratum' (based on the sq. root of $\sqrt{3}$ and $\sqrt{2}$ respectively) were considered to be necessary for the proportioning and coherence of medieval churches. 'Ad-triangulum' is when the section of the building is defined by equilateral triangle while in 'ad-quadratum' the height of the building equals the width. Villard de Honnecourt attempted to define the forms of living beings through pre-established geometrical figures. These figures can be categorized only by the respective numbers of their sides and not by their characteristics. His was geometry of numbers and not of measures i.e. the proportional relations of the different sides of figures, the relative angles between them were not taken into consideration. The geometrical methods given by Plato as mentioned in Book IX of Vitruvius' (1960) [44] discusses the doubling and halving a square area accurately by using geometrical methods as it was not possible to get accurate results by using arithmetic. The qualities of irrational numbers like $\sqrt{2}$, golden section (ϕ) and similar others were also exploited through geometry to signify the desired meaning.

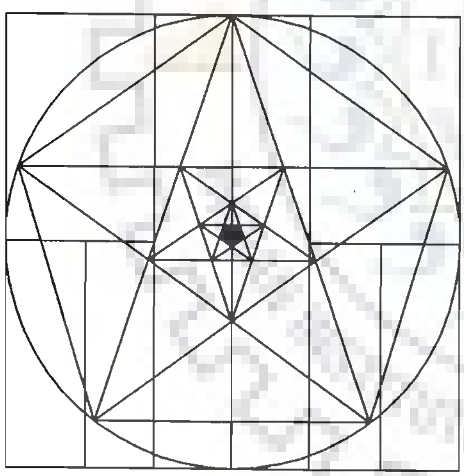
Giuseppe Vaccaro (1955) [82], in his analysis of Romanesque Churches like Lucca Cathedral, Basilica of S. Ambrogio, Milan etc. affirms the conscious use of these geometrical alignments that led to the harmony of forms in these churches. These systems of proportioning were the standard means of designing gothic cathedrals. Ghyka (1977) [31], reveals circle as the controlling figure of gothic architecture. She explains it through the examples of F.M. Lund and Prof. Moessel (a Munich architect). In Lund's diagram, pentagons or pentagrams are superimposed over the rectangular section of the naves. The centers of these figures coincide with the focal points like apse or alter in the section. [Figure showing Lund's diagram of vertical section of gothic cathedral of Cologne type showing the widths of naves and pillars interlinked through circles & pentagrams.]

The well-known example is Milan cathedral whose contemporary drawings and reports of the council of Milan were available. In 1386, it was decided to build a grand cathedral in Milan. In 1392, in a meeting it was decided to build according to 'ad-triangulum'. Mathematician Gabriele Stornalocco associated in this work shows triangular framework of the church in his sketch. Shortly afterwards the design was changed to 'ad-quadratum'. According to Wittkower (1953) [83], by that time the construction had already been started according to 'ad-triangulum' and was continued up to the piers of aisles. In both the schemes, the elevation seemed too high. The council decided to switch over to another geometrical method. Keeping the lower part, the design of the upper part was modified with the help of 3-4-5 triangle and the overall height was brought down. Ghyka (1977) [31], reproduced the elevation of the dome of Milan Cathedral originally published in 1521 by the architect – in -charge of the dome, Caesar Caesariano. Ghyka mentions that this diagram shows the function of concentric circles and the appearance of

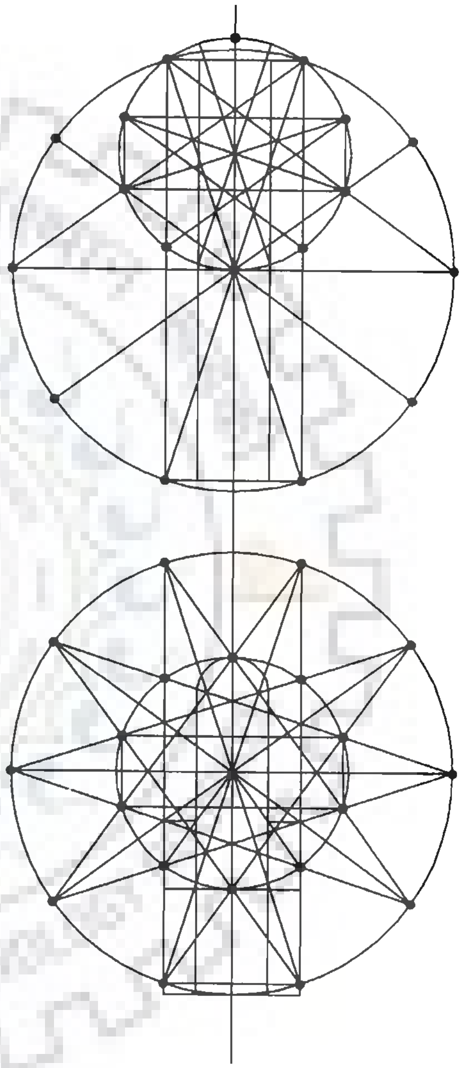


Construction of Human Figure, from Villard de Honnecourt, c , 1235 (Padovan , 2001)





Lund's Diagram Showing Vertical Section of A Gothic Cathedral of The Cologne Type , in Which Width of The Nave And That of Pillars Are ConnectedBy Interlinking Circles AndPentagrams. (Ghyka , 1977)



After Moessel , Two Gothic Standard Plans (Ghyka , 1977)

Fig 2.3 (b) GOTHIC GEOMETRY

words like 'symmetria' and 'eurhythmia' written at the top in Latin along with the use of $\sqrt{3}$ proportion in the geometry of the building.

"It appears that triangulation or the grid of squares formed the geometrical skeleton of cathedrals like Charters, Reims, Amiens and Cologne" (Wittkower, 1953) [83]. Padovan (2001) [48] emphasizes the significant use of number seven, due to its symbolic importance, in association with six, nine or twelve in his analysis of the proportions of Charters cathedral rebuilt between 1194 and 1224. Taking the height of the building from plinth to keystone, he claims the use of 3-foot module as all the dimensions in elevation according to him are multiples of it. He assumed the use of Cretan foot (= 320 mm) and Roman foot (= 294.45 mm) as basic foot measures in elevation and plan respectively during the rebuilding of this cathedral, which spanned oven thirty years. He further speculates that the main space comprised of nave with aisles and the chancel is contained within three cubes volumetrically.

Geometry in middle ages was directed to seek the ultimate truth. The fundamental relation of mathematics and astronomy which, hither to, was one of the basis of development of both does not seem to find much significance here as in the earlier ages. Mathematics was submitted to theological interpretation through geometrical and number symbolism.

2.6. RENAISSANCE ARCHITECTURE

Renaissance Architecture was an age of revolution. It started from Florence in Italy spread to Rome and then to other parts of Europe. Classical texts and remains were studied and understood thoroughly. Fresh investigation of Nature started on the basis of harmonious world-view offered by Pythagorean and Platonic theories but it did not reject Aristotle. The invention of printing press helped expanding the knowledge of antiquity. A new attitude for art, architecture and science started developing.

Whereas in the middle ages the primary building task were churches, the local priests or rulers were given as designers and the name of architects unknown, in Renaissance, the building tasks included secular buildings, private villas apart from churches which were still the primary tasks. The church was impregnated with symbolic meaning submitted to the glory of the God. The glory was also shared by artists, architects and their patrons. Attempts were made to redefine architecture first by Alberti around 1450 AD through his ten books of architecture. In his books he strongly advocates the Platonic world-view, which was essentially mathematical in nature. Alberti also mentions the invention of Perspective in his 'Treatise on Painting' for the first time though it was systematically experimented by Brunelleschi. Other authors also studied and write profusely about the approach towards art and architecture based on antiquity. Padovan (2001) [48], writes that Renaissance architects used the same proportions which govern the way the buildings were seen in perspective. He quotes Wittkower who claims that Leonardo stated that music and perspective share same harmonies. Perspective affects were intentionally created with the help of columns in the buildings of many fifteenth century Italian architects. It is this development and use of perspective space, which separates Renaissance from the classical period. According to Padovan, mathematics of perspective and proportions were the means of discovering and representing the world and were not considered as mere technical skills. They became central to architecture and painting. The platonic world-view of harmonious ratios existing in the universe and their three means (arithmetic, geometric and harmonic) formed the basis of proportioning system during the Renaissance. Alberti mentions the musical ratios as the audible proof of the same ratios prevailing the universe and advocates the use of the same ratios in architecture. The Christian belief of the Man as the image of God recognized human being in the center of the world. Human body was considered to be extremely beautiful and interesting, worthy of anatomical dissection. The proportions of the human body were applied to different parts of architectural form thus uniting the human body with the building "And just as the human body is a microcosm of the building, the building is in turn a microcosm of the city. Thus the city itself can be conceived as a great body, as Francesco di Giorgio represents it in a famous drawing (1470-80). Body, house, city and cosmos are all representations of each other, each ordered according to the hierarchical plan with head, body limbs and so on "(Padovan, 2001) [48].

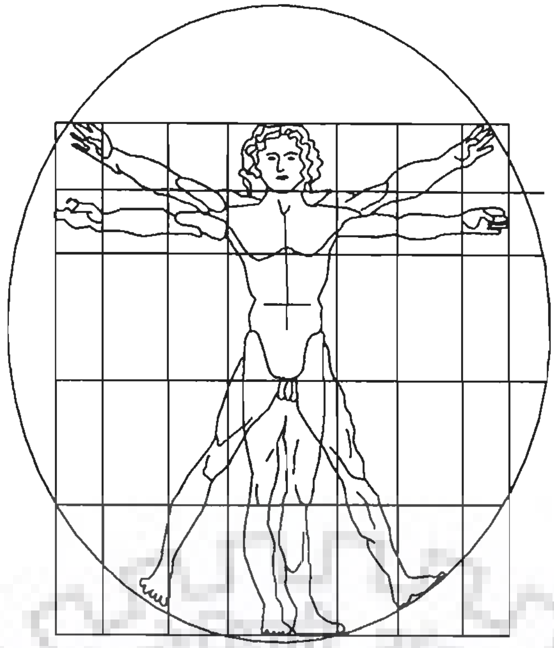
Vitruvius' description about man inscribed perfectly in square and circle mentioned in Book III found its best representation in Leonardo Da Vinci's drawing. This concept was expressed in the design of centralized churches like Brunelleschi's S. Maria degli Angeli, Alberti's S. Sebastino, Mantua.

Various authors mentioned different shapes of churches all emphasizing on centralized planning which resulted from the changed philosophical approach towards the representation of God in church architecture. Beauty was given preference over the necessities of the service. Alberti mentions that circle is the most preferred figure in nature followed by other regular figures like hexagon, square, octagon etc.

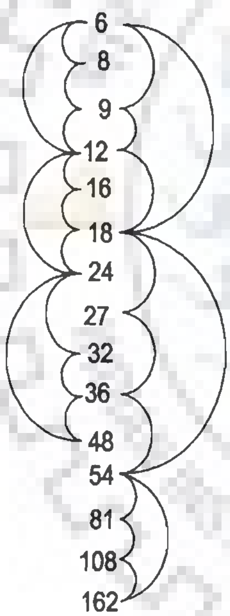
St. Peter's planned by Bramante is an example of the centralized planning integrated with Greek cross. The whole is confined in a large square with four apses projecting out from the center of four sides. Renaissance architecture is architecture of addition. The buildings vary from simplest to complex configurations. Each part is integrated to the other parts and with the whole without loosing its basic geometry. Though symmetry was not an explicit requirement of Renaissance architectural theory however most of the buildings were symmetrical either in plan or in elevation or in both.

"The conviction that architecture is a science and that each part of the building, inside as well as outside, has to be integrated into one and the same system of mathematical ratios, may be called the basic axioms of Renaissance architects" (Wittkower, 1952) [66].

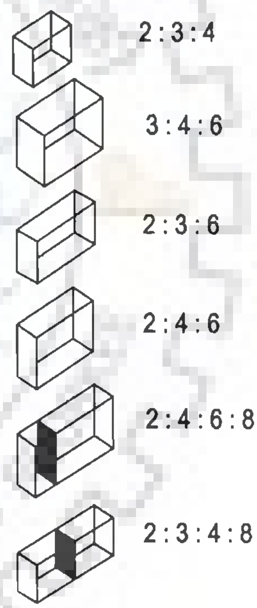
In 1525, Francesco Giorgi, in his texts blended Christian doctrines and Platonic ideas. In his design for S. Francesco della Vigna all the proportions of various parts of church and interrelations are expressed in the musical ratios of 1:2:3:4. The ratio of width and length is 1:3, Giorgi divides it in the form of 1:2 and 2:3, at its length respectively emphasizing the divisions with important placements. He generated two simple ratios 1:2 and 2:3 from the compound ratio 1:3. In this way the length was charged with definite relations. Alberti gave the theoretical details of this method. The compound ratios of the double, the triple and the quadruple are formed from the simple consonant ratios. Alberti emphasized the use of those sub-ratios, which correspond to the compound ratio. He also recommended the use of arithmetic, geometric or harmonic means of the lengths and breadths of the spaces in determining the height of the spatial volumes. This was further explained by Francesco Giorgi



Human Figure Describing Circle And Square After
Leonardo da Vinci ,1485 - 90 (Padovan 2001)



Arithemetic And Harmonic Divisions of
Double And Triple Intervals After F.
Gorgi, 1525 (Padovan , 2001)



Alberti , Recommended Proportions
For Rooms (Padovan , 2001)

Fig 2.4 RENAISSANCE GEOMETRY

in 1525, Giorgi Illustrates Plato's 'lambda' with double and triple intervals all multiplied by 6 to remove fraction, subdivided by arithmetic and harmonic means, combined in a continuous series with intervals and subintervals indicated by arcs.

Andrea Palladio (1965) [49] also endorses the heights of the rooms in his "Four Books of Architecture" based on one of the three means taken from antiquity. In the villas designed by Palladio the dimensions of the space are in harmonic series as in Villa Godi at Lonedo and Villa Malcontenta. Palladio states that the convenient numerical expression of geometrical mean is not always possible. According to Stevens (1990) [60], Alberti and other early writers used proportioning in subtractive way i.e. they started with rectangular shapes of plans or elevations and then subdivide them into harmonious ratios to create the sizes of different elements resulting in varying module sizes but regular shapes while Palladio joined the different elements of harmonic ratios to form the whole which may or may not be rectangular in shape.

Previous architects employed proportions either for the two dimensions of a façade or three dimensions of one part of the building; but it was Palladio who integrated different parts of the building in harmonic proportions. The uses of irrational numbers in Renaissance proportions were also witnessed in the works of different architects. Though Alberti favored whole number musical ratios but he did not deny the use of irrational numbers in proportioning systems. Some well-known villas of Palladio also witness the use of irrational proportions like $1:\sqrt{2}$, $1:\sqrt{3}$ in its spaces apart from the application of whole number ratios in other designs. The shapes of the rooms were circle, square, square – and – a half, square – and – a third, double square, $\sqrt{2}$ rectangle, other shapes derived from square roots of two and three etc. He did not exclude the use of incommensurable ratios in his theory. The development of musical theory in the sixteenth century added more consonant ratios to the existing Pythagorean ratios. These ratios include minor third (5:6), major third (4:5), minor sixth (5:8), major sixth (3:5), major tenth (2:5), minor tenth (5:12), eleventh (3:8), minor and major above the octave (5:16 and 3:10) etc. The introduction of these simpler ratios were aimed to replace the complicated ratios that arise with the Pythagorean scale such as the hemi one (256/243) and major third (81/64). The use of these ratios by Palladio can be witnessed in his Villa Pisano at Bagnolo and other buildings.

We can conclude that Renaissance architects applied both types of Platonic mathematics i.e. mathematical or whole number system as well as geometrical system of proportions in their architecture.

2.7. HINDU ARCHITECTURE

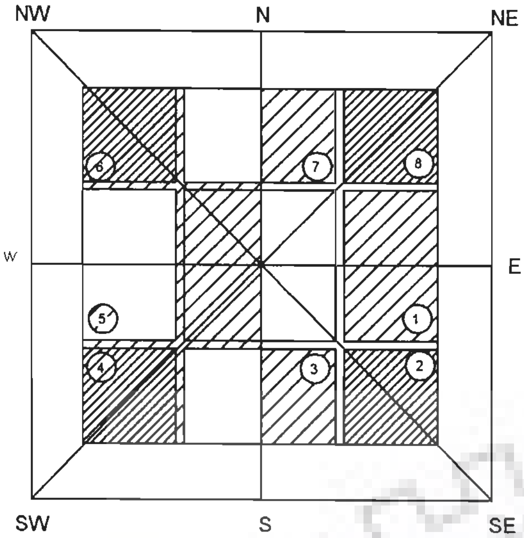
Hindu architecture originated and chiefly refers to the architecture of the Indian subcontinent. The architecture of this subcontinent can be mainly categorized into three phases starting from the Indus Valley civilization around 2500 BC to the Aryan invasion around 1500 BC followed by the second phase till the invasion and gradual conquest of Mohammedans i.e. up to 13^{th} Century AD. It is this phase which witnessed the growth and development of Hindu architecture from 10^{th} to 18^{th} century AD till the establishment of British administration.

The sacred treatises called 'Vedas' in the form of hymns and invocation of Aryan deities were written around 1000 BC. Gradually the Dravidian deities were associated with Vedic culture. While Aryan gods were formless, Dravidians represented the Supreme Being through Idols and fertility symbols. From the fusion of these two faiths, Hinduism developed in its typical form. The first philosophical treatises the 'Upanishads' came into existence around 800 BC. 'Brahman' was the unformed ultimate TRUTH, the eternal self the Supreme God who was the cause of the universe, the omnipresent, self-luminous being, the final eternal power, the only reality. The 'unformed' Brahman manifested as 'formed' Brahma or Ishvara is regarded the creator, orater and destroyer of the universe. Different deities are the product of this imagination representing the varied attributes of the Supreme Being who encompasses all of them.

The science of architecture 'Vastu Vidya' was already a part of occult knowledge in vedic times but was written systematically during middle ages when hindu temple building and rituals associated with it became complex and rules associated with proportions became numerous Stella Kramrisch (1976, Vol. I) [38], mentions that the science of architecture, Vastu-sastra, also known as Sthapatya-sastra-Veda was enumerated as Upveda, a lesser applied knowledge subordinating 'Atharvaveda'. 'Atharvaveda' is one of the four chief sacred treatises of Hinduism. As per Vastu-sastra, any building of whatever size and whatever purpose was built according to the magical figure called Vastu Purusa Mandala (VPM). This geometric figure of Vastu Purusa Mandala (VPM) assumes cosmological, metaphysical, geographical, astronomical and architectural significance. Vastu Purusa Mandala consists of three words: Vastu, Purusa and Mandala. Vastu is any existing thing in its orderly state in which human being dwell. Ground is the main Vastu laid out in the image of Cosmic Man called Purusa. Cosmic Man or Supreme Being here assumes a form. It becomes identical with the planned site. Mandala refers to any closed polygon. Mandala is an area with focal point as center and clearly defined boundaries. VPM thus represents the image of the cosmic model. “Although this ritual diagram is neither the ground plan of the temple nor necessarily the plan of the site, it regulates them. It is drawn on the ground prior to the building of the temple and on it the temple stands either in fact or symbolically “(Kramrisch, 1976 vol. I) [38].

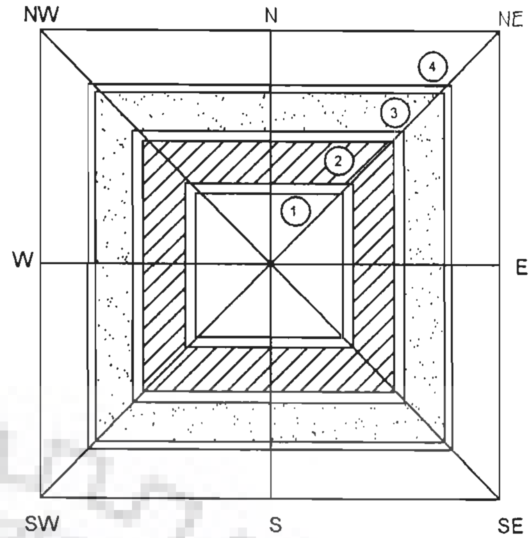
A square is most preferred shape for VPM owing to its metaphysical significance. It is considered to be the perfect form depicting the Supreme Being. Earth as manifestation of God is thus represented by square but from mundane, physical form, it is represented by circle. However VPM can also assume triangular, hexagonal, octagonal and circular shapes of equal area in architectural compositions.

VPM establishes the proportional relations of the ground plan as well as the vertical section of the building relating the horizontal and vertical measures with each other. For large areas, it can regulate the disposition of different buildings while in a single building; it can proportionally relate different parts with each other. Prabhu and Achyuthan (1997) [53], expound that the above mentioned shapes were also used in combination to generate axially oriented forms with rectangle and apsidal forms with semi-octagon and semi-circle. They further explain that a square mandala can be analyzed in two ways, first by dividing the square into smaller grids called ‘padas’ by means of intersection of orthogonal lines at regular intervals and second through the enveloping paths formed by concentric lines called ‘Vithivinyasa’.



1 Purva 2 Agni 3 Daksina
4 Nirriti 5 Pascima 6 Vayu
7 Uttara 8 Isana

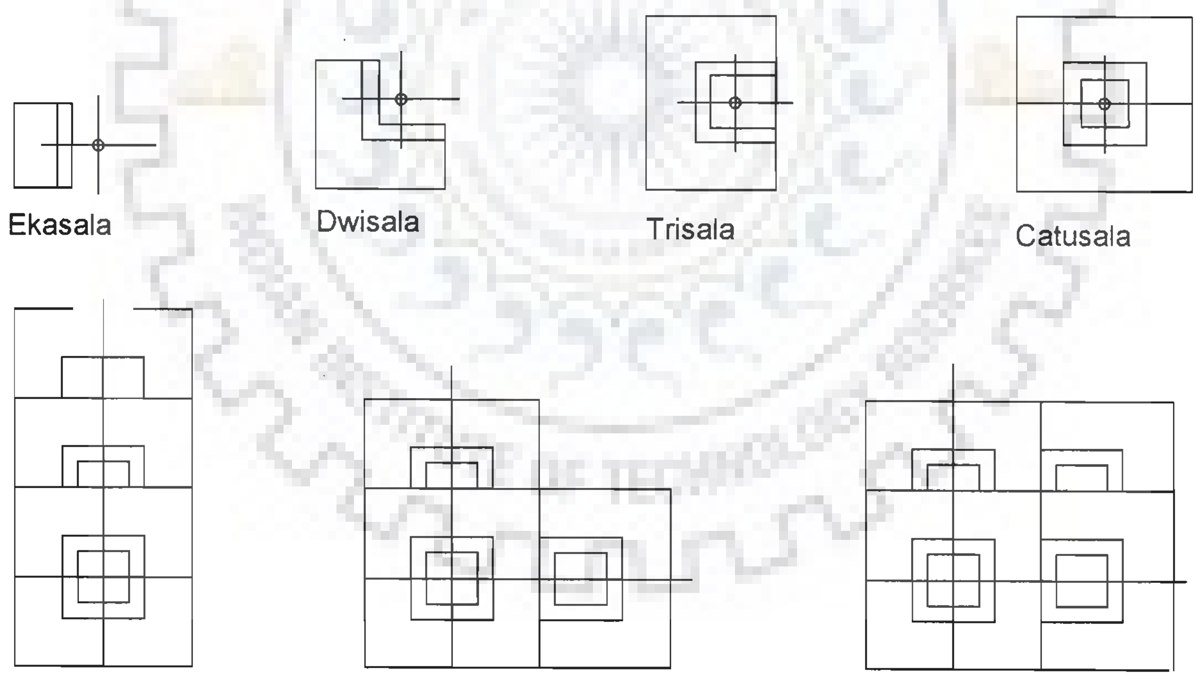
Grid Analysis (Padavinyasa)



1 Brahma Vithi 2 Deva Vithi
3 Manusya Vithi 4 Pisaca Vithi

Analysis By Envelopes (Vithivinyasa)

Two Methods of Analyzing Mandala



Ekasala Dwisala Trisala Catusala

Uniaxial Growth Biaxial Growth Fully Develloped Form

Development of Form Based On Modular Geometry

Fig 2.5 HINDU GEOMETRY
Prabhu & Achyuthan (1997)

The former is called 'Padavinyasa' system, applied mainly for houses and the later 'Vithivinyasa' system employed for expanding structural complexes like temples, settlements etc.

In the Padavinyasa system, the number of padas can vary from 1 to 1024. Thus number of padas on any one side of square may vary from 1 to 32. There can be 32 number of square mandalas each having its own name. Kramrisch (1976,vol. I) [38] mentions that the square mandalas having 1,2,3 and 7,8,9 padas on one side are the most significant, the others can be constructed as reductions by analogy or by amplifications of these six plans.

The padas are assigned their individual gods. The central most assigned to God Brahma. The inner most ring occupies the most important gods while the outer rings occupy the gods of lower celestial hierarchy as we move away from the center. 44 deities are assigned to the mandalas of 64 and 81 padas. Four inner gods surround the Braham-Sthana; eight middle gods occupy the next outer ring and 32 gods are assigned the outer most ring.

Mandalas of 7,8 and 9 padas on one side of the square are chosen for houses and palaces. For town 8 and 9 pada –sided mandalas were more significant as bigger mandalas can be formed out of them.

Volwahsen (1969) [65], discusses that the town was planned as exact rectangle in outline with main streets running from north to south and east to west along the lines which divide padas from each other. The outer wall of the town was erected on the outer boundary of the mandala. The dwelling blocks were produced by the division of the padas. Only the main thoroughfares, which give the city, its basic form were need to confirm closely to the divisions of VPM.

Remainder has a special significance in Indian architecture. Kramrisch (1976, vol.1) [38], describes it as a germ or material cause for what subsists. Indian system of proportions depends heavily on the remainder because it is through the remainder that the structure gains astronomical, astrological and metaphysical harmony with the universe. “The Indian doctrine of proportion is designed not only to correlate the various parts of a temple in an aesthetically pleasing manner, but also to bring the entire building into a magical harmony with time and space as well as with the caste of the builder...the central element in the doctrine is that each temple must correspond to six magical prerequisites ”(Volwahsen, 1969) [65]. The width and length of the proposed structure keeps on varying till the desired harmony with time and space is achieved. The orientation of the structure in any of the eight possible cardinal points is determined by ‘Yoni’. According to Prabhu and Achyuthan (1997) [53], by dividing the prime dimension of the proposed structure by eight, the remainder called Yoni will determine the orientation of the building, Yoni number vary from 1 to 8, starting clockwise from east. These authors also discuss differences among various texts regarding the choice of the prime dimension. If the remainder is 1, it is called ‘Dhwajayoni’ belonging to ‘Purvavastu’ i.e. Vastu located towards the east of the center, ‘Brahmanabhi’, facing towards west, While Volwahsen (1969) [65] ,describes Yoni as a result of multiplication of width by three and then dividing this by eight. Yoni here varies from 0 to 7 where ‘0’ indicates orientation towards east.

Prabhu and Achyuthan (1997) [53], further mention the convenient units chosen for the computation of Yoni so as to get the remainder as a whole number. These describe the dimensional system used in traditional Indian architecture.

Prabhu and Achyuthan (1997) [53], expound that there were three tiers of measurement systems based on grain size (yava), the digit size (angula), the anthropometric measure. These octal system of units are related as:

Table 1: OCTAL SYSTEM OF UNITS

		1 tila	=	0.469 mm
8 tila	=	1 yava	=	3.75 mm
8 yava	=	1 angula	=	30.00mm
8 angula	=	1 pada	=	240.00 mm
8 pada	=	1 vyama	=	1920.00 mm

(Source: Prabhu and Achyuthan-'Design in Vastuvidya', 1997)

1 tila = the diameter of the til oil seed - the smallest unit.

1 yava = grain of wheat variety.

However for practical purposes derived units like parva, vitasti, hasta, danda, rajju, nadika, and yojana were employed

TABLE 2: DERIVED UNITS

1 parva	=	3 angula	=	90		
1 vitasti	=	12 angula	=	360mm		
1 hasta	=	24 angula	=	3 pada	=	8 parva ;720 mm
1 danda	=	4 hasta	=	8 vitasti	=	2.88m
1 rajju	=	8 danda	=	32 hasta	=	23.04 m
1 nadika	=	1000 danda	=	4000 hasta	=	2.88 km
1 yojana	=	8 nadika	=	1000 rajju	=	23 km

(Source: Stella Kramrisch- 'The Hindu Temple',1976) angula is the length of middle portion of the middle figure

angula can be further categorized as

Uttama = 8 yavas

Madhyama = 7 yavas

Kanista = 6 yavas

vitasti is the distance between thumb and middle figure duly stretched.

hasta is the distance between elbow and tip of the little finger.

The materials of construction were stone, brick, timber and mud. The superior buildings were constructed of stone or brick, the medium ones used brick or timber and the inferior structures used mud.

1 pada was the basic module used for wall construction, the doors & windows were measured in hasta units, further smaller modules were 3 angulas, then one angula and its goes up to yava in finer derails. Yoni calculation was done for each component, specifying the unit's selection for prime dimension to calculate 'Yoni'. For larger dimensions, modules were rajju, danda, vyama.

Kramrisch (1976, vol.1) [38], discusses various texts in relation to the proportionate measures of the temples from 6th to 9th AD: though different texts suggest different proportions but most commonly the module of proportions were based on either architectural measure or it was fixed in relation to the main cult object (image). Primarily the outer width of the square Prasada (the main temple) was taken as the basic architectural module for horizontal and vertical measurements, secondarily the inner width of Prasada could also be taken. The interrelationships among horizontal and vertical dimensions, among various smaller measurements followed geometrical progression. Prominently Octave (1:2, 2:4) was the leading ratio for different measures together with Fifth (2:3) as the suggested total height of the temple. This means the total height of Prasada could be three times that of width out of which two-third of the total would be the height of upper portion 'Shikhra'. In the second case, where the module is the cult object the vertical dimensions of the image was taken. The main architectural parts were again interrelated with arithmetic or geometric series in the ground plan and geometric or harmonic series in the interrelationships of plan and vertical section of the building. The same theme of Octave and Fifth musical ratios was followed.

In the early eleventh century architectural treatise 'Samaranganasutradhara' modifications in the proportions of Prasada is described. The proportions witnessed in the earlier temples were no longer observed in the vertical dimensions but they were still followed in the plan. With the gradual additions in the temple spaces subsidiary to Prasada, new set of rules were formed to regulate the vertical dimension which were stated in the above mentioned treatise. The width of the Prasada was not the only architectural module now but few other dimensions were also fixed as smaller modules in addition to the same basic module of width to determine the vertical dimensions.

The other structure called 'Mandapa' (pavilion) added to Prasada had the same basic architectural module for the determination of its proportions-Mandapa could be rectangular or square whose central portion was defined by four columns. The same above mentioned proportions were followed for Mandapa in plan and in other small measures but its height was not fixed as it was dependent upon the height of the temple.

Kramrisch (1976,vol.1) [38], explaining the proportions of South Indian temples mentions that the treatise 'Isanasivagurudevapaddati' compiled between 9th and 11th century AD is the key to the complexities of proportions of South Indian temples. Kramrisch further discusses in detail the distinction between different categories of temples. This distinction was based on the size and the complexity of their types. The area of inner sanctuary (Garbhagrha) having 64 or 81 squares related itself to Vastumandala. The height of smallest single-storey shrine is twice its width divided into eight parts; four of which are perpendicular wall and remaining four are the upper parts of superstructure. These two main divisions are further subdivided into three parts each in octave proportions as 1:2:1, 1:2:1.

Kramrisch describes five kinds of proportionate measurements for South Indian temples taken from the text 'Vaikhanasagama'. These are:

Santika : $H = 1\frac{3}{7}W\left(\sqrt{2}W\right)$; The peaceful

Paustika $H = 1\frac{1}{2}W$; The successful

Jayada $H = 1\frac{3}{4}W$; The Joygiver

Adhbuta $H = 2W$; The supernatural

Sarvakamika $H = 2\frac{1}{8}W$;the all-desired

This text shows the variation of height from $1\frac{3}{7}W$ to $2\frac{1}{8}W$ but as a rule the height never exceed twice the width of Prasada in small shrines while in larger temples it was $1\frac{3}{7}W$ which is the diagonal length of square with side W.

The proportionate measures listed in different texts are not the same as seen in the proportion of height & width of a Dravida Temple below.

Table 3 : Proportion of Height and Width of a Dravida Temple

	Vaikhanas-agama	Isanasiva-gurudeva-padhati	Samaran-ganasutra-dhara.	Mayamata	Kasyapasilpa	Manasara	Silparatna Mayamata
Santika	H = 13 /7 W	H =1 3/7W	$H=W\sqrt{2}$	1 3/7	1 4/5	H = w	1 3/7
Paustika	H = 1 1/2 W	H = 1 5/7W		1 3/6	1 5/6	H =1 ¼ W	1 ½
Jayada	H= 1 3/4W	H= 1 6/7W		1 3/5	1 6/7	H = 1 ½ W	1 3/4
Sarvaka mika	H =21 /7W			1 ¾	2 1/8	H =1 ¾ W	W
Adbhuta	H = 2W	H =2W		2W	2W	H=2 W	2W
Abhicara							3/4 W

(Source: Stella Kramrisch- 'The Hindu Temple',1976)

Prabhu and Achyuthan (1997) [53], referring 'Mayamata' mention that these proportionate measures were not restricted only to the temple but were used in other types of buildings and hence can be considered as general measures. Hindu architecture seeks beauty through the practice of canons of Vastusastra. According to Kramrisch, canonization of forms were more predominant in the works of Indian architect rather than doing justice with the qualities of the materials.

2.8. ISLAMIC ARCHITECTURE

Islam regards human being as an image of the cosmos. The sacred architecture – Mosque architecture – is the replica of the cosmos and a designated place for the encounter of man with the Divine Word or Logos. The architecture of the house, the palace and practically any architectural unit up to the scale of town and country planning dealing with everyday life is an extension and inspiration of the sacred principles of Islamic architecture based on the relationship between man and cosmos in its traditional sense. In this way, Islamic world has generated a unity of purpose and principles in all its manifestations, which bind them together. It experiences a quality of 'sameness' in its architecture through out its length and breadth despite numerous stylistic variations owing to specific time and /or region. The common language is created by the fundamental similarity of elements and forms. This common language was subjected to abstraction because of the rapid diffusion of the Islamic culture following political conquest. Islam shuns representative figural forms; the language of abstraction chosen was therefore geometry. Emphasis on geometry is the fundamental constituent of Islamic society, the architect-planner known as 'muhandis' – is the one who geometricizes. A strong emphasis is laid on the study of mathematics, science of nature and alchemy in the traditional Islamic education. 'Numbers, lines, shapes and colors provide coherent modes of articulation for the awakened soul that seeks external expression" (Ardalan and Bakhtiar, 1973) [5].

The concept of number in Islam is impregnated with qualitative aspect apart from being a quantitative entity; the science of number is the root of everything, standing above nature as a way of corresponding unity thus manifesting similarity with the Pythagorean system. Understanding in this sense, numbers are associated with certain external shapes. Geometry is regarded as the 'personality' of numbers for further exploration into the processes of nature. The number 1 creates the point, 2 the line, 3 the triangle, 4 the square while 5 is the circular number and 6 is the cube.

The triangle is the first enclosed space configured from points or lines symbolically represents the link between heaven and earth. Two triangles one pointing upwards and the other pointing downwards comprise the seal of

Solomon representing the tendencies of all forms and the actions of the four elements.

The square is the most externalized and static aspect of creation that becomes cross and dynamic when extended. Cube is the symbol of man among matter and earth among planets. It is the supreme temporal symbol because Ka'bah means cube.

The circular number 5, generated from cross and the centre represents the wheel of heaven. Circle is the most perfect shape. One, as creator, is the point moves through two, as the line, acting as a radius creates sphere, the evident symbol of unity. This division of sphere by inscribed regular polygons forms the basis of all traditional laws of proportions. "Each number and figure, when seen in its symbolic sense, is an echo of unity and reflection of a quality contained in principle within that unity, which transcends all differentiation and all qualities and yet contain them in a principle manner" (Ardalan and Bakhtiar, 1973) [5].

In traditional architecture, the square of earth is integrated with circle of heaven thro' the triangle which is the link embodying both aspects. The transformation of the circle through the triangle into the square is the fundamental theme. The primitive pendentives of the Sasanian 'Chahar taq' (a domed tetrapylon structure) are the bold example of it.

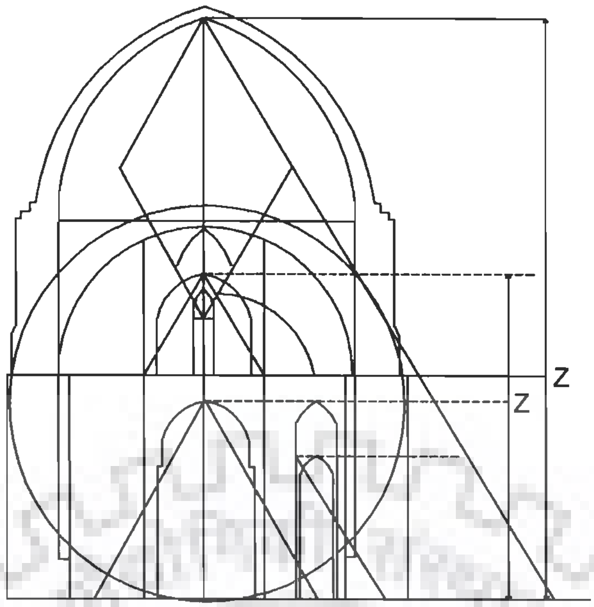
The most characteristic example of the interaction between circle and square is the 'mandala' – a cosmogram envisioned as Garden of Paradise; works through number and geometry.

Square plan of Ka'bah also found in courtyards and buildings is the reflection of quadrangular temple of Paradise, octagonal drums of mosques are intermediary forms above the square base reflect the image of the Divine Throne apart from its structural function of forming a device to place circular dome above it, dome is the vault of heaven and the spiritual world beyond it. The geometrical shapes not only fulfill architectural functions of material order, they are representation of higher reality.

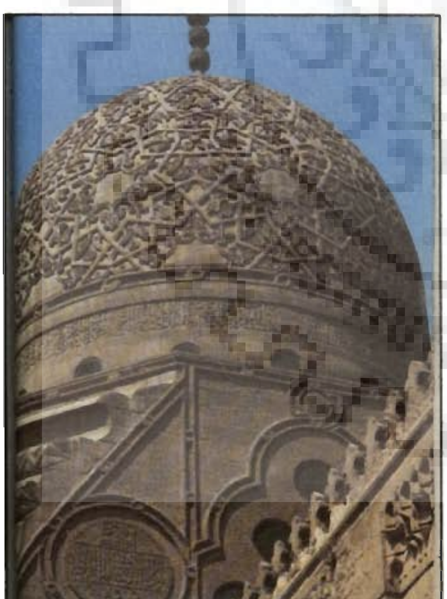
In the Islamic geometry the five regular solids that can be inscribed in a sphere are cube (composed of six squares), icosahedron (composed of twenty equilateral triangles), octahedron (of eight equilateral triangles) and dodecahedron (composed of twelve pentagons). These are the same solids known to us from Greek period as 'Platonic bodies'. Islam ascribed the same symbolic reference to the first four viz earth, water, air and fire respectively as given by Plato while the fifth one dodecahedron represents here universe as a whole.

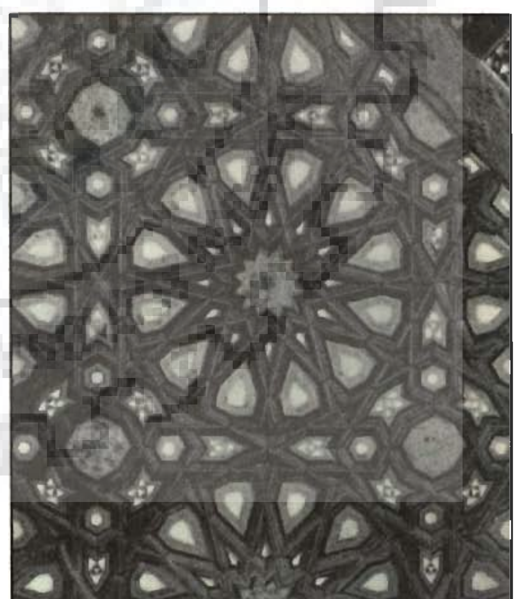
The ratios that occur frequently in the generation of pattern –plan are that of side of a square to its diagonal (i.e. 1: $\sqrt{2}$) creating series of squares expanding along their diagonals, and the golden section $(1:1.618....)$ occurring from pentagon and pentagram extensively found in recurring themes of man and nature. According to Ardalan and Bakhtiar (1973) [5], the golden mean, developed in a series of whole integers 1,1,2,3,5,8,13,21...i.e. Fibonacci series was introduced into Europe from Islamic world by the translation of an Arabic text by an Italian merchant Fibonacci in the thirteenth century.

Golden section has been employed in the system of proportions in setting out the perfect small dome chamber of Jami mosque in Isfahan. The governing shape in plan is often reflected in the pattern of the star-vault which is the inner side of the dome. Square grid was an active design tool; it



Golden Mean Employed in Setting Out
The Small Dome Chamber of Jami Mosque, Isfahan (Ardalan And Bakhtiar ,1973)





Geometrical Patterns Embellish Wall Surfaces

Fig 2.6 ISLAMIC GEOMETRY

determines the actual dimensions of plan and height of the building apart from serving as a basis for articulation of facade with the help of determinant ratios used in design.

Modularity was another quality related to the system of proportioning and use of grid. The unit square of the grid was determined according to the size of the smallest module the 'brick'. Geometrical patterns are another example of modularity where endless patterns are generated from few basic shapes as modules.

Monumental mausoleum raised in the memory of an exceptional person is another building type in which the expression of geometry is significant. It projects individual's status, built according to the current structural and decorative techniques. It usually consisted of a cube crowed by a dome, signifying a reality symbolizing the Islamic conception of world, therefore, is an expression of the function. At Dome of Rock in Jerusalem, a dome stands above octagonal substructure is basically an elaboration of the cube-dome theme.

The Cube theme is also apparent in Ka'bah at Mecca. "…and because of its form, the Ka'ba manifests the basic directions of space: the cardinal points, the Zenith and the Nadir. Here the cube is complimented by the dome of the sky itself, rather than by a built symbol. The presence of the circle, however, becomes manifest in the surrounding floor pattern." (Norbergschulz, 1986) [77].

Horse-shoe arch may be characterized as one of the typical motifs of Islamic architecture apart from complex form of 'muqarnas' used for transition from plane to curved surfaces. Light accentuates the general feeling of integration and unity. "The primary manifestation of Islamic architecture is, therefore, consists in a comprehensive "character" rather than a set of district figural elements." (Norbergschulz, 1986) [77].

Geometric patterns for two-dimensional decoration are developed from basic figures using the principles of symmetry, rotation, modularity and transformation along with the use of complex mathematical ratios at some places. Geometrical patterns are used as space filling surface patterns, which grow side by side. The three regular polygons, the triangle, the sphere and the hexagon are the basic shapes forming patterns in three regular i.e. diagonal, right angled and circular lattices. These polygons have been used in variety of space filling combinations, submitted to the central purpose of manifesting unity in traditional Islamic architecture. The configurations of these endless repeated patterns combining space and time depend upon the place where they are generated, floor consists of square patterns representing earth, the walls have the resolution of the circle to the square while the roof is embellished with circular centripetal lines symbolic of cosmos. The geometric patterns depend less on the natural attributes of materials, the structural organization of surfaces promote form. Arabesque patterns combine the fluidity of nature with the geometric transfiguration of surfaces. These motifs generate variety of circular patterns developing on single or multiple planes. These natural patterns float in relief in the passive or neutral geometric compartments.

Like many ancient civilizations man is the unit of measure of Islamic space. Six is considered to be the complete number expressing the proportional height of the body. It is considered as the number of the body.

The fundamental measuring units are cubit, foot, palm and finger. The distance from the elbow to the tip of the figures is one cubit or six palms; width of the palm is four fingers. The finger or the digit equals six barley placed side by side while sixteen fingers or four palms makes a foot.

2.9. POST- RENAISSANCE SCENARIO

The ancient mathematical systems of order in art which dominated up to renaissance became questionable in the period about eighteenth century. The seventeenth century science revealed that the universe was governed by simple mathematical laws, which can be easily adapted and discovered by human mind. Universe was conceived as the perfectly functioning machine and a creation of divine intelligence. The nature of universe as revealed by science became completely abstract and mathematical devoid of any harmonic relationship to the world of senses.

According to Padovan (2001) [48], the decline in the renaissance canons of proportions in Mannerist and Baroque art and architecture occurred a century earlier than the influence of the development of Baroque science. The abandonment of proportional rules coincided with and to some extent preceded the development of new cosmology. The atomist universe comprised of two things: space and time, which are like containers and matter and motion, are their respective contents. The universe became purely abstract and intangible known only through mathematical equations with no connection with the sensory experience.

The conception of Baroque unity and fluidity can be discerned in mid-sixteenth century in the works of Michelangelo (1475-1564) and Tintoretto (1518-94) half a century before Galileo and more than a century before

Newton. Michelangelo's attitude towards the human body as a dynamic structure was in sharp contrast with other renaissance artists like Leonardo Da Vinci and Albrecht Durer who were fascinated by Vitruvian bodily proportions. Michelangelo asserted that all arithmetic and all rules of proportion are useless without the observing eye.

It therefore seems that the sixteenth and seventeenth centuries experienced a general shift from static to dynamic, from the limited to the infinite and continuous space. This concept affected every aspect of culture and art. Science and art started becoming increasing insulated from each other. The ancient relationship between the application of mathematics in art and in science was disrupted. Padovan (2001) [48], states that it was art that broke this relationship. The architect Claude Perrault (1613-88) rejected the old doctrine of equivalence between musical harmony and visual proportions and tried to construct system of proportions based on knowledge and reason. He distinguished two kinds of beauty, one which was universal based on convincing reasons, the other arbitrary that depended on prejudice. The former one comprised 'symmetry' which resulted due to collective relationship of parts because of balanced correspondence of their size, number, disposition and order while the latter one was determined by our wish to give a definite proportion, shape or form to things that appear agreeable merely by custom. The former proportion corresponds to Vitruvian 'symmetry' and the later one corresponds to 'eurhythmy', being a matter of shapes and forms of separate elements. Like Perrault, the baroque architects Guarino Guarini (1624-83) and the neoclassicist Francesco Milizia relied heavily on the eye of the perceiver, allied to experience as the only basis of proportion.

The new philosophy of proportions in art and architecture evolved in Britain. Perrault's rejection of musical theory was followed by the Painter William Hogarth and the architect Sir John Soane. Similarly David Hume and Edmund Burke dismissed the age old belief that proportions were the cause of beauty. This resulted in the reduction of artistic discussion to the matters of taste. From this point onwards started growing the nineteenth and twentieth century tendency in which the objective and universal standards in the judgment of art is replaced by the subjective and personal ones. Beauty believed to lie strongly in the eye of the beholder. The attention now shifted from the interpretation of physical world to the study of mental processes and of the grounds of human knowledge. This shift from outer to inner world had important consequence on the theory of proportions in art.

The corpuscular – kinetic explanation of the external world given by Newton in his 'Principia' in 1687 and initiated by Galileo and Gassendi at the beginning of the century had a profound effect and marked a turning point. It reigned for next two hundred years until overthrown by Einstein in 1915.

In the making of the world of art, artist's individual choice was no longer guided by the mathematical laws or the laws of nature or even by social convention. Artist's instinctive judgment took the lead in creative decisions and the role of reason was limited only to serve it in the practical sphere by choosing technical means appropriate for the desired ends.

Berkeley and Hume both argued that apart from relying on the perception of eye for the judgment of beauty, the beauty of proportion must be subject to the consideration of utility. Hume's conclusions were different from Berkeley. Berkeley argued that the judgment of good proportion must be made by reason through the means of the sight while for Hume proportion does not depend on reason; it lies in the eyes of the beholder. It is psychological in nature, and depends on individual character and disposition. Art must submit to rules which are discovered by intuition of the individual artist or by 'observation' of that which has generally been found pleasing at all times and places.

Edmund Burke (1729-97) also associated beauty with the strongest emotions in his treatise and rejected the doctrine of beauty connected with mathematical rules of proportion. He also dismissed the argument that mathematical proportions are the cause of beauty in plants and animals on the grounds that these exhibit infinite variety of proportions yet we consider them equally beautiful. He attacked at the Vitruvian notion of proportion in architecture derived from the human body and specifically from the circumscribing square and circle which it generates on the reasons that such posture is strained, unnatural and unbecoming; he mentions that this posture gives rise to a cross and not to a square. According to Burke we do not borrow proportions from nature but impose them on it. Immanuel Kant (1724–1804) concludes that nature or reality is something which we can know and it is not determined by the external laws. All phenomena accordingly to Kant are a human construction distinct from the external world. Looking in this way, architectural proportions can therefore be regarded as the creations of the human mind and not the quality of the thing in itself.

The Rediscovery of the Golden Section

Padovan (2001) [48], describes that the earliest use of the name 'golden section' or golden Schnitt appeared to have been used in 1835 in Ohms' treatise 'Diereine Elemantare Mathematik'. Adolf Zeising was the first to state the golden section as the underlying secret of all the natural and artistic forms in 1854 in his book "New Theory of the Proportions of the Human Body". He established golden section as the universal law underlying all the creations and operations in botany, zoology, astronomy, physics, chemistry and finally to human and artistic proportions. According to Zeising the golden section is a 'goal' to which human body aspires in its physical proportions as it attains maturity.

Twenty years after Zeising, Gustav Theodore Fechner (1834-87) another German, founded the science of experimental aesthetic. This experimental approach was based on the current trend of aesthetic speculation in Germany inclined more towards psychology and away from philosophy. He used three different kinds of experimental approach which seemed to establish convincingly the aesthetic supremacy of the golden section. The repetition of the same ratio between two parts of a line, of that between whole line and its bigger part was the reason of ideal balance of unity and variety which is responsible for its aesthetic pleasure. Also the fact that golden rectangle consists of a square and its own reciprocal had been the key factor of its perceived beauty as seen by some researchers. Because of the beautiful simplicity and its occurrence in so varied phenomena, the golden section came to be regarded by the early years of twentieth century as synonymous to beauty of proportions.

Theodore Cook in his 'The curves of life' (1914) discovered that the ϕ spiral formation is a common factor in the growth of shells, plants, animals and human being. He revealed that the same ratios and shapes are valid both in science and art because both are inevitably shaped by investigating human mind. Cook's most important innovation is the introduction of ϕ progression as an infinite series. He also showed the close connection between ϕ progression and Fibonacci series. "Each successive power of ϕ is composed of various sums of the unit andϕ, the proportion between the two being a ratio between consecutive Fibonacci numbers. Thus:

$\phi^2 = 1 + \phi$

$\phi^3 = 1 + 2\phi$

$\phi^4 = 2 + 3\phi$

$\phi^5 = 3 + 5\phi$

$\phi^6 = 5 + 8\phi$

$\phi^7 = 8 + 13\phi$

and so on.

Cook clams that this 'new mathematical conception' is the best formula for the hypothesis of Perfect Growth..." (Padovan, 2001) [48].

He also applied this ϕ progression to the proportions of human body and proposes the system of ϕ proportions similar to Le-Corbusier's taking the standard height of man as 68 inches. But it was Le-Corbusier who went far beyond putting systems of harmony and proportion as the main theme of his design philosophy based on his belief in the mathematical order of universe closely bound with golden section and Fibonacci series.

In his early painting and buildings, he based his composition on 'regulating lines'. The 'regulating lines' were the diagonals of rectangular parts of facades which by their parallelism and perpendicular intersections resulted in the recurrence of one or a few shapes through out the whole composition. The composition was therefore ordered by the recurrence of few similar rectangles out of which golden rectangle was the preferred figure.

Immediately after First World War there was a widespread emphasis on standardization and mechanization of buildings which again got prominence in 1940s at the time of creation of Corbusier's 'Modular', where he established the connection between system of proportions and standardization. The use of golden section can be witnessed in the early houses of Le-Corbusier. The most apparent embodiment of this proportion is seen in Villa stein at Garches, 1927. The two main facades of the house are approximate golden rectangles. The golden rectangle can be seen even in the small features of this building also.

The 'Modulor' is based on the measure of the body as an embodiment of golden section - natures' fundamental proportion. 'Modulor' is a scale of dimensions fixed by the height of a six foot man constituting two interwoven ϕ geometric series called red and blue series. The red series is the primary one with initial value of 1830 mm. The ratio by which each number increases or decreases is ϕ i.e. 1.618.... Therefore the series moves forward and backward from 1830 mm to get numbers of one's choice.

... 270 430 700 1130 1830 2960...

Now 270 + 430 = 700, 430 + 700 = 1130, 700 + 1130 = 1830 and so on which makes a Fibonacci series

Han Vander Laan (1983) devised his proportioning system for architectural use. He claims that it arises from the way we perceive space. "The key lies in the measurements that appear distinct from one another. Vander Laan uses a series related to Fibonacci sequence but with a slightly different rule

1,1,1,2,2,3,4,5,7,9,12,16,21,...

$P_i = P_{i-2} + P_{i-3}$ for $i > 2$ given P_0, P_1 and P_2 "(Stevens, 1990) [60].

Here the fourth is the sum of the first two in any sequence of four terms. The ratio between successive terms approach the value 1.325.... as the terms grow larger. The value 1.325... is called 'the plastic number' and is one solution to the cubic equation $1 + x = x^3$

1.325... is the fundamental ratio between two terms in the geometric series.

$$1 \quad \frac{4}{3} \quad \frac{7}{4} \quad \frac{7}{3} \quad 3 \quad 4 \quad \frac{21}{4} \quad 7$$

Laan claims that the plastic number is based on three dimensions instead two. The series only approximates geometric one as the eye cannot distinguish between exact and approximate lengths in this sequence. It consists of rational numbers rather then irrational ones. There are eight terms in the series and the whole plastic number set consists of three series where the smallest of one is the largest term of the preceding series. The smallest is the thickness of wall and the largest would be 7^3 or 343 times wall thickness. Taking wall thickness of 150mm (6 inches) the three orders end in 1050 mm (42 inches), 7350mm (24 ft 6 inches) and the largest dimension is nearly 51.5 m (171 ft).

In the three orders the first is suitable for the dimensions of a house, the second for a court and the third for a town-square. Stevens (1990), further discussed that unlike 'Modulor', this system of proportions deals purely in architectonic and objective way. However, the application of this system is yet to be seen practically.

2.10. CONCLUSIONS

Architectural proportions give measures to our spatial environment which we experience in our daily life. They are least concerned with the scientific revolution of the seventeenth century or the changed philosophy of the eighteenth. The ancient world view of finite mathematically ordered cosmos was undermined by developments in science and nature became abstract human construction. It, therefore, becomes even more important now to apply a mathematical order in our works of art as it is embodied in the methodology of science.

CHAPTER 3

THE GEOMETRICAL SYSTEMS EXPLAINED

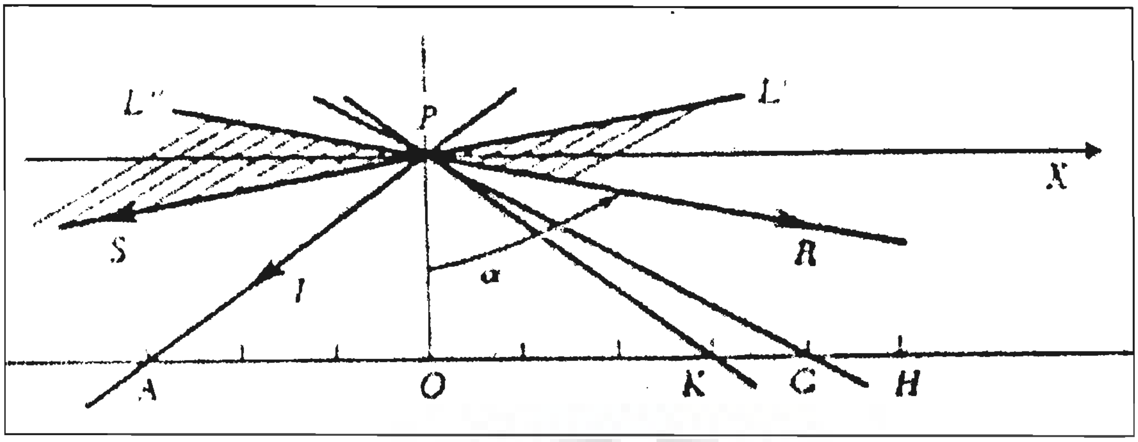
3.0. INTRODUCTION

There are different versions about the development of geometry in history. Some scholars ascribe that this development took place in Asia specifically in Indian subcontinent and Central Asia and then the knowledge of geometry was taken to Greece while others are of the opinion that the development of geometry took place in and around Greece. Broadly speaking we have two types to geometry with us in practice:

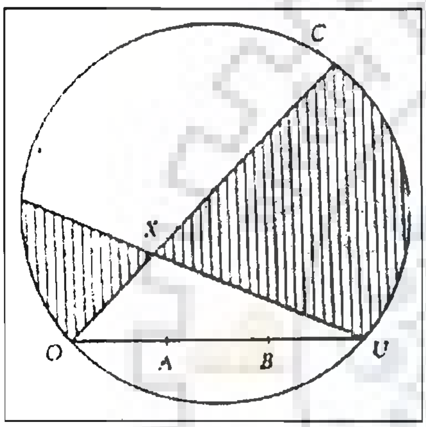
i) Euclidean geometry

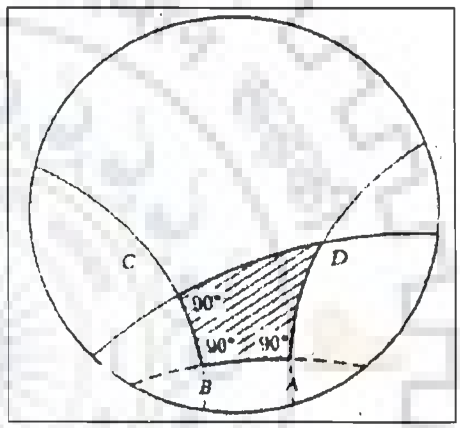
ii) Non-Euclidean geometry

Euclidean geometry named after Greek mathematician. Euclid. Euclid in his book 'Elements' written in approximately 300 BC, started from a set of statements considered to be indisputably true. From these statements he then derived conclusions. From these conclusions further set of conclusions can be derived. 'Elements' discusses reasons, logics and method of deduction. Euclidean geometry discusses space as a number of relation of different points. Euclid discusses the fundamental properties of shapes and sizes of objects. Parallelism and congruency were the basic postulates. Congruency deals with 'equivalence' of different figures with each other. The parallel axiom and the axiom that a straight line is infinite in length are practically unprovable as both extend into the realm of infinite space. Euclid also developed a model known as 'Euclidean Model' showing his work along with these axioms.



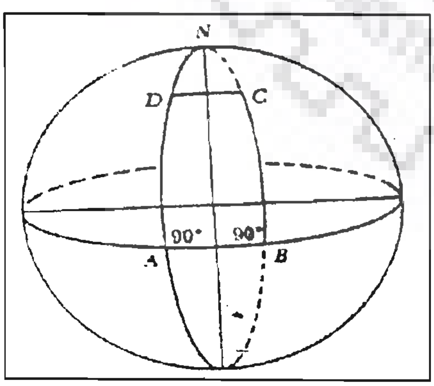
Euclidean Model

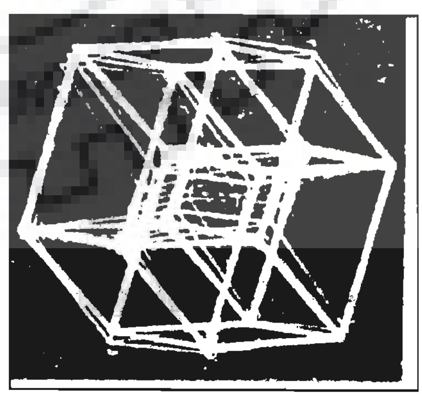




Klein Model of Parallel Lines In a Plane
Spatial Elliptic Geometry Requires
3 - Dimensional Sphere

Development of Hyperbolic Parabolic Geometry





Development of Elliptic Geometry

Computer Generated 4 - Dimensional model

Fig 3.1 DEVELOPMENT OF NON-EUCLIDEAN GEOMETRY
Ekta Mehta (2001)

Archimedes and Appoloniam further extended the development of geometry. Archimedes' contribution lies in the development of areas and volume.

Non–Euclidean geometry results from new set of axioms which challenge Euclidean postulates. The new axioms were developed in 19th century though many such attempts were made in earlier centuries. "Through a given point not on a given line, more than one line can be drawn not meeting the given line" was the new axiom. Through such developments, the new system Non-Euclidean in nature was born, named as hyperbolic geometry. After that other Non- Euclidean geometrical systems appeared. The major among there was elliptic geometry developed by Riemann (1826-66) and then by Felix Klein (1849-1925). It rejected the postulate of parallelism and state that every line is endless and finite in length.

Einstein's theory of Relativity is based on Riemann's' geometry. Then arose the theory of orthogonal arcs followed by projective geometry. Two intersecting circles are orthogonal if their tangents at a point of intersection are perpendicular. All the new theories extended deeper insight into the nature of space. Today space is simply a set of elements such as distance between two of them. A new development in modern mathematics is topological space based on topology.

The basic addition to our conventional perception of space is the addition of 4th dimension. During the first three decades of 20th century, 4th dimension was a common concern for artists. In1970, both artists and mathematicians gave visual forms to spatial fourth dimension. Banehoff and Strauss manipulated intricate four dimensional figures on the computer.

Whereas the theories of η-dimensional space are in the process of development by mathematicians, architecture combining the realm of feeling and thinking continue to progress in three-dimensional space broadly based on the following geometrical systems resulting in meaningful environment :

i) Mathematical proportions

ii) Golden Proportions

iii) Geometrical proportions

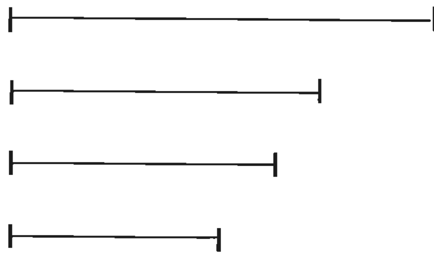
iv) Regulating lines

v) Module-based proportions

vi) Preferred Dimensions (The Modular)

3.1. MATHEMATICAL PROPORTIONS

These were first discovered and discussed by Greeks. They believed that order in architecture is a result of combining numerical ratios in some regular ways. Pythagoras discovered these numerical ratios in the harmonies of music. Later on he concluded that these mathematical ratios are beautiful in themselves and the harmonies of music are just one consequence of this mathematical beauty. He experimented these ratios in music by taking two strings in the same degree of tension, dividing one of them by half (means the lengths of two strings are in the ratio 1:2) and then by plucking both the strings he found the pitch of the shorter string exactly one octave higher than the longer one. He further explained that when the length of the two strings are in ratio 2:3, the difference in pitch is called fifth and when the lengths follows the ratio 3:4, the difference in pitch is a fourth.



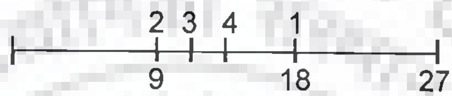
1/1 whole string

3/4 (Diatessaron) fourth

2/3 (Diapente) fifth

1/2 (Diapasson) Octave

Thus the whole Greek musical harmonies can be expressed in the ratios 1:2:3:4. Another consonance which the greeks recognized was the octave plus a fifth, where 9:18 = 1:2, an octave, and 18:27 = 2:3 a fifth



Plato summarized it as a set if numbers whose relationships with each other determine all the interdependent harmonies in the universe of space and time. He introduced the concept of mathematical proportion by explaining the function of proportion as binding things together. The two things called 'extremes' can be glued together with the help of a third called 'mean'. Now placing in sequence these three terms, the first extreme, the mean and the second extreme, form a proportion. The ancient mathematicians Nichomachus and Pappus each list 10 kinds of means of which 9 are common to both making eleven together. Matila Ghyka (1977) [31], describes all ten types of proportions established by neo-Pythagorean school.

Example

i) $\frac{c-b}{b-a}=\frac{c}{c}$ (1, 2, 3)… arithmetic proportion

ii) $\frac{c-b}{b-a}=\frac{c}{b}$ (1, 2, 4) … geometrical proportion

iii) $\frac{c-b}{b-a}=\frac{c}{a}$ (2, 3, 6) … harmonic proportion

iv) $\frac{b-a}{c-b} = \frac{c}{a}$ (3, 5, 6)

v) $\frac{b-a}{c-b} = \frac{b}{a}$ (2, 4, 5)

vi) $\frac{b-a}{c-b} = \frac{c}{b}$ (1, 4, 6)

vii) $\frac{c-a}{b-a} = \frac{c}{a}$ (6, 8, 9)

viii) $\frac{c-a}{c-b} = \frac{c}{a}$ (6, 7, 9)

ix) $\frac{c-a}{b-a} = \frac{b}{a}$ (4, 6, 7)

x) $\frac{c-a}{c-b} = \frac{b}{a}$ (3, 5, 8) … Fibonacci series

Of all these proportions, Plato favored geometrical proportion the most.

The three most common means are: the arithmetic mean, the geometric mean and the harmonic mean.

The 'arithmetic mean' B is the middle of the two extremes A and C so that B divided both their sum and their difference into two equal parts such that

$$B = \frac{A+C}{2}$$

In arithmetic proportion, the difference between each of the two neighboring terms is constant e.g. 1, 2, 3.

The 'geometric mean' B between A and C is such that A: B = B: C, geometric mean B between A and C is also equal to the square root of their product so that

$$B = \sqrt{AC}$$

The 'harmonic mean' B is that middle term between A and C that divides their difference in the same ratio as the two terms have to each other i.e. In harmonic proportion, the third term is exceeded by the same fraction of the second and the second by that of the first e.g. 6:8:12. The harmonic mean B between A and C is such that:

$$B = \frac{2AC}{A+C}$$

Padovan (2001) [48], adds another mean called 'Contra harmonic mean' to these three most commonly used means. Contra harmonic mean divides the difference between two extremes in the opposite way to the harmonic mean, that is, in the inverse of the ratio that they have to each other,

here $$B = \frac{A^2 + C^2}{A+C}$$

Stevens (1990) [60], describes three theorems about the means as:

i) The geometric mean of two numbers is also the geometric mean of two other means

i.e. $GM = \sqrt{HM.AM}$

ii) Given a harmonic series a, HM, b

Then $\frac{1}{a}, \frac{1}{HM}, \frac{1}{b}$ is the arithmetic progression

iii) AM > GM > HM

Where AM = Arithmetic Mean

GM = Geometric Mean

HM = Harmonic Mean

With the development of musical theory during 16th century more consonances were added by Ludovico Fogliano, through experience, in 1529 to the existing musical consonances. These were minor (5:6) and major third (4:5), minor (5:8) major sixth (3:5), and major (2:5) and minor tenth (5:12), eleventh (3:8), major and minor sixth above the octave (5:16 and 3:10). Zarlino, a venatian, in mid sixteenth century provided a scientific approach to the whole harmonic system received from antiquity. He explained that consonances are determined by arithmetic as well as harmonic mean. "The arithmetic mean 3 between 2 and 4 divides the octave in fifth (2:3) and fourth (3:4), the same result, inverted, is achieved by the 'harmonic' mean 8 between the extremes 6 and 12 (6:8 = 3:4 and 8:12 =2:3). Zarlino could show that the same law to the division of the fifth, for 2:3 or 4:6 with the arithmetic mean 5 determines the ratio of major and minor that (4:5 and 5:6) and with the 'harmonic' mean – as in 10, 12, 15 – the ratios of minor and major third is possible; the insertion of the arithmetic mean between 4 and 5 leads to the ratio 8:9:10, 8:9 being the major tone and 9:10 the minor tone, while the harmonic mean 80 between the extremes 72 and 90 divides the series into minor and major tone" (Wittkower, 1952) [66].

Andrea Palladio himself was convinced of the universal validity of the same harmonic system. His buildings incorporated the ratio 3:5, 4:5 and 5:6 and other similar ratios not only in the dimensions of one room but also in the relationship of one room with the other apart from the use of already existing Greek musical ratios. Colin Rowe (1947) [58], comparing Palladio's 16th century Villa Malcontenta with Le-Corbusier's 20th century Villa Stein at

Garches proved the use of same mathematical proportions in different periods of history.

3.2. GOLDEN PROPORTIONS

Two ratio between the two sections of a line or the two dimensions of a plane figure where the smaller of the dimensions is to the greater as the greater to the whole length i.e. the sum of the both

If 'a' is the longer side and '1' is the smaller, then

$$\phi = a : 1 :: (a+1) : a$$

or $$\frac{a}{1} = \frac{a+1}{a}$$

$$\Rightarrow a^2 - a - 1 = 0$$

$$\therefore \quad a = \frac{\sqrt{5+1}}{2} \simeq 1.618$$

$\phi(Phi)$ is called the golden ratio. The name Phi is derived from Phidias, the sculptor of Parthenon. Renaissance writers called this as 'divine proportion'.

ϕ has many interesting properties.

$$\phi = \frac{\phi+1}{\phi} \Rightarrow \phi^2 = \phi + 1 \simeq 2.618$$

$$\phi - 1 = \frac{1}{\phi} = \frac{\phi}{\phi+1} \simeq 0.618$$

Golden proportion has many interesting geometric & algebraic properties because of which it is very extensively used in architecture.

As discussed by Ghyka (1977) [31] about ϕ:

$$\phi = \frac{\sqrt{5+1}}{2} = 1.61803398875\ldots \text{(so 1.618 very accurate approximation)}$$

$$\phi^2 = 2.618\ldots = \frac{\sqrt{5}+3}{2}$$

$$\frac{1}{\phi} = 0.618 = \frac{\sqrt{5}-1}{2}$$

$\therefore$ $\phi^2 = \phi + 1$; $\phi^3 = \phi^2 + \phi$ and more generally

$$\phi^n = \phi^{n-1} + \phi^{n-2}$$

(this also applies to negative exponents so that :-

$$\phi = 1 + \frac{1}{\phi} \text{ or } \phi^1 = \phi^0 + \phi^{-1}$$

$$\phi^{-2} = \phi^{-3} + \phi^{-4} \text{ or } \frac{1}{\phi^2} = \frac{1}{\phi^3} + \frac{1}{\phi^4} \text{ etc.)}$$

We also have:

$$2 = \phi + \frac{1}{\phi^2} \text{ and } \phi = \frac{1}{\phi - 1}$$

$$\phi = 1 + \cfrac{1}{1 + \cfrac{1}{1 + \cfrac{1}{1 + \cfrac{1}{1 + \dots}}}} \qquad \phi = \sqrt{1 + \sqrt{1 + \sqrt{1 + \sqrt{1 + \dots..}}}}$$

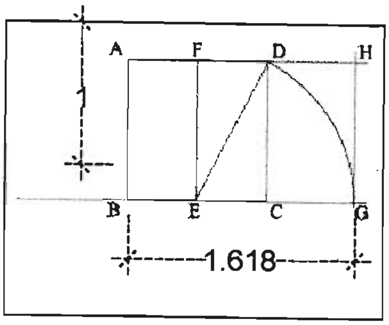
A rectangle whose sides are in ϕ relation is called golden rectangle. If we construct a square inside of this rectangle on its smaller side, the remaining rectangle left inside the original one will also have the similar golden proportions as the original rectangle had. If we infinitely repeat the process of creating squares and similar golden rectangles then during transformation their sizes decrease but the proportions of each part remain similar to its corresponding other parts and to the whole. This phenomenon of 1 : ϕ rectangle is called 'whirling squares'. D'Arcy Thompson (1975) [63], calls this as 'Gnomons'.

Renaissance writers claimed golden rectangle as the aesthetically perfect rectangle. Three golden rectangles join to make the corners of an icosahedron and centre of the faces of a dodecahedron. Any progression based on golden proportion is additive and geometrical. Fibonacci series 1,1,2,3,5,13,18,...based on whole numbers is closest to ϕ progression. In Fibonacci progression, every term is the sum of the two preceding terms; the ratio between any two consecutive terms tends to approximate golden ratio as the series progresses towards infinity. Similar in the geometrical progression $1, \phi, \phi^2, \phi^3, \ldots \phi^n$ each term is the sum of two preceding terms. It is this property of being additive and geometrical at the sometime which signifies its role in living organisms as mentioned by Ghyka (1977) [31].

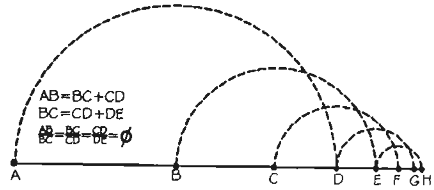
Also in the diminishing series 1, $\frac{1}{\phi}, \frac{1}{\phi^2}, \frac{1}{\phi^3}, \ldots \frac{1}{\phi^n}$, each term is the sum of two following terms i.e. $\frac{1}{\phi^n} = \frac{1}{\phi^{n+1}} + \frac{1}{\phi^{n+2}}$ and $\phi = \frac{1}{\phi} + \frac{1}{\phi^2} + \frac{1}{\phi^3} + \ldots \frac{1}{\phi^m} + \ldots$ where 'm' grows indefinitely.

So golden proportions are very useful is design where the chain of related proportions produce similar shapes because of the property of any geometrical progression of ratio ϕ or $\frac{1}{\phi}$ e.g. ϕ, $a\phi$, $a\phi^2$, $a\phi^3 \ldots a\phi^n$ or $a, \frac{a}{\phi}, \frac{a}{\phi^2}, \frac{a}{\phi^3} \ldots \frac{a}{\phi^n}$.

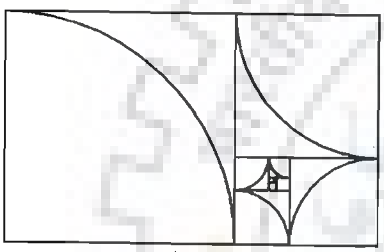
Ghyka (1977) [31], gives geometrical illustration of this particular property of ϕ or $\frac{1}{\phi}$, which combines the quality of additive and multiplicative, geometrical series, that is a series of straight segments with lengths



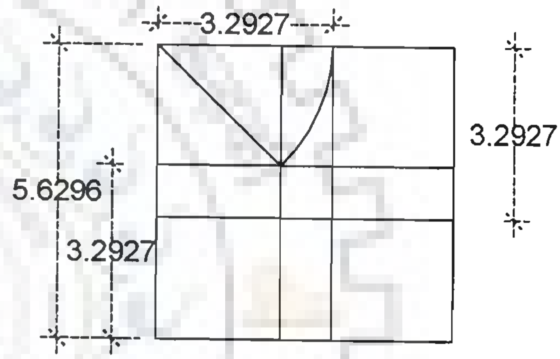
Generation of Golden Section
From The Diagonal of Half Square



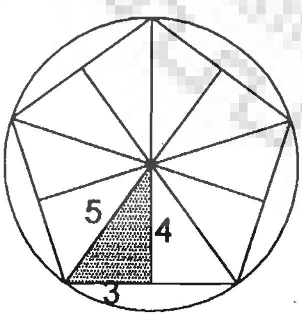
Diminshing Series of Segments ,
With Ratio 1/phi , Having
The Unit Of Measure
As First Term

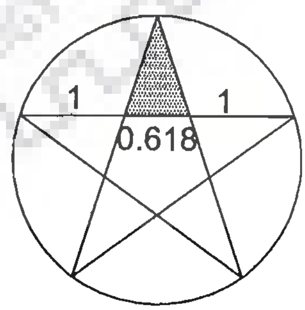


Spirals of Harmonic Growth



The figure Has Three Different Shapes,
Nine Figures Can Be Found In It,
And Uses Only Two Dimensions





Pentagon & Pentagram Showing Pythagorean Triangle & Golden Section Proportion
(Doczi, 1994)

Fig 3.2 GOLDEN PROPORTIONS

proportional to the terms of this series which can be constructed by additions or subtractions of segments by simple moves of the compass.

Golden section is predominantly found in the proportions of the human body. In a well built body, the ratio of the total height to the vertical height of the navel is always $\phi(=1.618...)$ or near approximations. It was rediscovered in 1850 by Zeysing, who found the importance of ϕ in animals, botany, in Greek Architecture and in music. The ϕ relationships in the various parts of human body were detailed out by Le-Corbusier in 1948 in his 'Le-Modulor' based on which he made two red and blue series.

Ghyka (1977) [31], further, explains that, based on Plato's 'Theaetetus' about 'dynamic symmetry' Prof. J. Hambidge established golden proportions in the best of Greek temples, vases, mirrors etc. The constructions of the regular pentagon and regular pentagram intimately depend upon this ϕ relationship. The construction of these figures discovered by Pythagoreans and given by Euclid is based on the formula.

$$p_r \text{ side of the regular pentagon} = \frac{R}{2}\sqrt{10-2\sqrt{5}}$$

If p_s be the side of the star pentagon or pentagram, d_r the side of the regular decagon, d_s the side of the star decagon, R the radius of the circumscribed circle, we have

$$p_s = \frac{R}{2}\sqrt{10+2\sqrt{5}} \text{ and } \frac{p_s}{p_r} = \frac{\text{Side of the pentagram or star pentagon}}{\text{Side of the regular pentagon}} = \phi$$

This establishes an important relation between the diagonal of the regular pentagon and its side.

$$\text{Also } d_r = \frac{R}{\phi},\ d_s = R\phi$$

The side of the regular decagon, the radius of the circumscribed circle and the side of the star decagon form ϕ progression of the three terms. Doczi (1994) [17], also extensively discussed the role of golden proportions in living organisms, plants and its specific role in the pentagon and pentagonal symmetry.

3.3. GEOMETRICAL PROPORTIONS

The geometrical proportions include the architectural proportions which can be constructed geometrically but can not be expressed in whole numbers. These also include the figures and polyhedra from which these can be constructed. Golden proportion can also be taken as a part of this but because of its own qualities and ordering capacity, it has been dealt separately. The irrational square roots of 2, 3 and 5 provide the basis on which architectural proportions are based. These irrational numbers can be constructed by simple figures involving the circle, the square and the right-angled triangle i.e. the primary geometrical figures. Ghyka (1977) [31], ascribes the essential symmetries in art and life to $\sqrt{2}, \sqrt{3}, \sqrt{5}$ relating $\sqrt{5}$ closely with ϕ.

THE SERIES OF REGULAR POLYGONS

As Padovan (2001) [48], describes the equilateral triangle embodies the square root of 3 the ratio of the height to half the base, the square embodies the square root of 2 as the ratio of the diagonal to the side. The regular hexagon is related to square root of 3 as the ratio of the height to the side. The 'double square' relates to square root of 5 as the ratio of the diagonal to the shorter side. Also 'double square' inscribed in a semi-circle given square root of 2 as the ratio of the diameter of the semi-circle to the longer side of the double square. Similarly a square inscribed in the half circle gives the ratio of a side of a square to the diameter as square root of 5. If we construct a rectangle whose height equals that of the height of the square and its width equals the diameter of the circle, if results in $\sqrt{5}$ rectangle. It results in two small golden rectangle plus a square or two overlapping golden rectangles.

Further among other polygons, the hypotenuse of a right angled isosceles triangle is square root of 2 if the other two sides are one unit long. The right-angled scalene triangle having shorter side as one unit and hypotenuse as two units has height equal to square root of 3.

Two rectangles in the ratio $1:\sqrt{2}$ join along the longer side make another $1:\sqrt{2}$ rectangle. Similarly halving $1:\sqrt{2}$ rectangle along longer side also results in two $1:\sqrt{2}$ rectangles. D'Arcy Thompson (1975) [63], calls such figures as gnomons. The photocopying paper of A-series form a geometric progression 1,2,3,8,6,..

THE FIVE REGULAR POLYHEDRA

Padovan (2001) [48], explains that these irrationals are the results of the ratio between the edge of the regular polyhedra and diameters of the spheres that touch either the centers of the edges (midspheres) or the apices (circumspheres).The regular tetrahedron shares the square roots of 2 and 3 in its construction. $\sqrt{2}$ is the ratio of the edge to the diameter of the midsphere, $\sqrt{3}$ is the ratio of the diameter of the circumscribing sphere to the diameter of the midsphere. In cube, $\sqrt{2}$ is the ratio of the diameter of the midsphere to the edge and $\sqrt{3}$ being the ratio of the diameter of the circumscribing sphere to the edge. Similarly regular octahedron makes $\sqrt{2}$ as the ratio of the diameter of the circumscribing sphere to the edge; while regular icosahedron results in golden ratio as the ratio of the diameter of the midsphere to the edge and finally regular dodecahedron embodies ϕ^2, as ratio of the diameter of the midsphere to the edge $\sqrt{2}$ is also the diagonal of the square side of cube, $\sqrt{3}$ is the ratio of the height to half the base of the equilateral triangle that forms the faces of the tetrahedron, octahedron and icosahedron.

Padovon (2001) [48], expounds upon a method called 'continued fraction' method by which these irrational numbers can be trapped between rational limits to desired degree of accuracy. The fractions which converge towards the values of this irrational number are:

$$\sqrt{2} = 1 + \cfrac{1}{2 + \cfrac{1}{2 + \cfrac{1}{2 + \cfrac{1}{2 + \dots}}}} \qquad \sqrt{3} = 1 + \cfrac{1}{1 + \cfrac{1}{2 + \cfrac{1}{1 + \cfrac{1}{2 + \dots}}}}$$

$$\sqrt{2} = \frac{1}{1}\ \frac{3}{2}\ \frac{7}{5}\ \frac{17}{12}\ \frac{41}{29} \qquad \sqrt{3} = \frac{1}{1}\ \frac{2}{1}\ \frac{5}{3}\ \frac{7}{4}\ \frac{19}{11}$$

The two alternate fractions that converge towards $\sqrt{5}$ are:

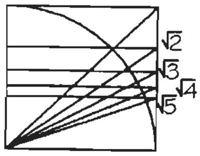
$$\sqrt{5} = 1 + \cfrac{2}{1 + \cfrac{1}{1 + \cfrac{1}{1 + \cfrac{1}{1 + \dots}}}} \quad \text{and} \quad 2 + \cfrac{1}{4 + \cfrac{1}{4 + \cfrac{1}{4 + \cfrac{1}{4 + \dots}}}}$$

$$\sqrt{5} = \frac{1}{1}\ \frac{3}{1}\ \frac{4}{2}\ \frac{7}{3}\ \frac{11}{5} \qquad \sqrt{5} = \frac{2}{1}\ \frac{9}{4}\ \frac{38}{17}\ \frac{161}{72}\ \frac{682}{305}$$

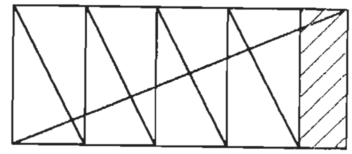
The successive approximate values for

$\sqrt{2}$ are 1.0, 1.5, 1.4, 1.4166…., 1.4138.

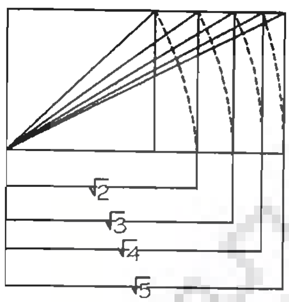
$\sqrt{3}$ are 1.0, 2.0, 1.6666……, 1.75, 1.7273…,1.7333…



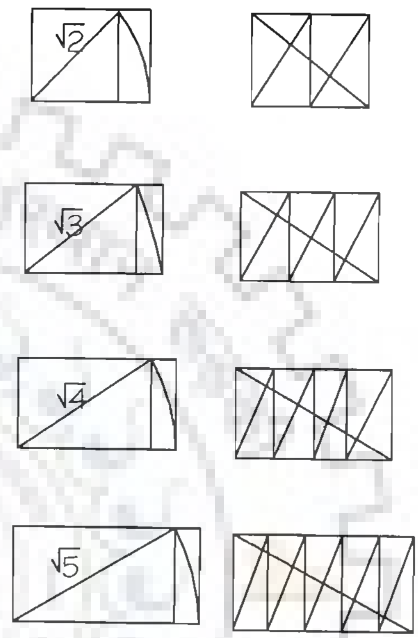
Square Root Rectangle Within The Square



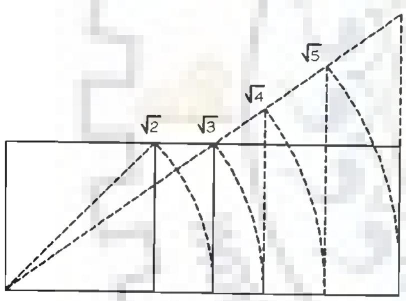
Imperfect Rectangle



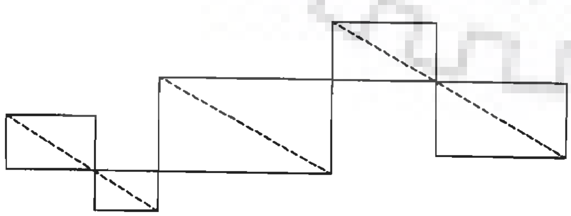
By Subtending The Diagonal of Square



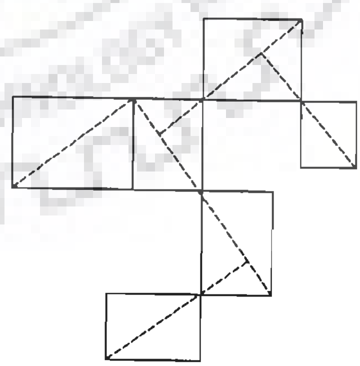
Perfect Rectangles



Old Method Before Hambidge



Law of Parallel



Law of Perpendicular

Method of Construction of Important Shapes in

Fig 3.3 GEOMETRICAL PROPORTIONS

calculated to seven decimal places

$\sqrt{2} = 1.4142135$

$\sqrt{3} = 1.7320508$

The successive approximation for $\sqrt{5}$ are

First – 1.0, 3.0, 2.0, 2.3333 … and 2.2

Second – 2.0, 2.25, 2. 2353 …, 2.2361… and 2.2360679

(calculated to seven decimals)

In the case of $\sqrt{2}$ and $\sqrt{3}$, the approximations are alternately below or above the actual value of the elusive square root. In the case of $\sqrt{5}$, the first series of values closely relates to golden ratio and Fibonacci Luca series, the denominators of the successive fractions form Fibonacci series while the numerators form Luca series as they converge towards golden ratio ϕ as limit while the second series approaches the limit more rapidly as described by Padovan (2001) [48].

Matila Ghyka (1977) [31], discusses the properties of the most common regular polygons along with their respective irregular but common figures:

Triangle : The equilateral triangle has an angle of 60^0 at all the three vertices. If't' be the side of the triangle, R be the radius of the circumscribing circle then

$$R = \frac{t\sqrt{3}}{3} \text{ and S = the surface of the triangle } = \frac{t^2\sqrt{3}}{4}$$

The other important non-equilateral triangles are

i) The Pythagorean triangle of sides 3, 4, 5,the right angled triangle whose sides are in arithmetical progression.

ii) The 'Great Pyramid' right-angled triangle whose sides are in the proportion $1:\sqrt{\phi}:\phi$. This triangle can be derived from 'Golden' rectangle; this is the only triangle whose sides are in geometrical progression.

iii) The isosceles triangle having angle of 36^0 at the sharp vertex and 72^0 at each of the base vertices. This triangle is found in pentagon, pentagram and decagon. In decagon, it is found by joining the centre to any of its sides. The ratio between the longer side and the shorter side of an isosceles triangle is ϕ.

Rectangle : ϕ rectangle is the most flexible shape available to us to create interesting proportions belonging to same symmetry. By drawing a diagonal from one corner to another and a perpendicular to it from any of the remaining two corners, we get the inner square on shorter side within a φ rectangle. This diagonal of a ϕ rectangle equals the side of star-pentagon / pentagram inscribed in a circle with the shorter side as radius. If 'a' is the length of this shorter side, then:

$$\text{diagonal, } d = a\sqrt{\varphi^2 + 1}$$

ϕ^2 rectangle is produced by adding a square on the shorter side of ϕ rectangle. ϕ^2 is the ratio between the longer and the shorter side. The diagonal of a double square rectangle is $\sqrt{5}$. Rotating this diagonal towards larger side, $\sqrt{5}$ rectangle is formed which is closely related to golden proportions.

By rotating the diagonal of a ϕ rectangle towards longer side, another longer rectangle is formed whose ratio between the longer and shorter sides is $\sqrt{\phi}$ = 1.273. Taking shorter side as 1, the longer side is $\sqrt{\phi^2 - 1} = \sqrt{\phi}$ as $\phi^2 = \phi + 1$. This rectangle can be divided into three similar rectangles; this process of division can be continued up to infinity. The surfaces of these rectangles form a geometric progression of $\frac{1}{\phi}$. The proportions, $\phi, \sqrt{\phi}, \phi^2, \sqrt{5}$, square and double square can be mixed as they belong to the same symmetry.

Pentagon and Decagon : The sides p_s and p_r of the pentagram and pentagon respectively form φ ratio between them.

The surface of the pentagon, $S_p = \frac{p^2 r}{4}\sqrt{5(5+2\sqrt{5})}$

The surface of the decagon, $S_d = \frac{5}{2} d^2 r\sqrt{5+2\sqrt{5}}$

If R is the radius of the circumscribed circle.

p_r side of the regular pentagon

p_s side of the regular star pentagon or pentagram

d_r side of the regular decagon

d_s side of the regular star-decagon

$$p_r = \frac{R}{2}\sqrt{10 - 2\sqrt{5}}$$

$$p_s = \frac{R}{2}\sqrt{10 + 2\sqrt{5}}$$

$$\frac{p_s}{p_r} = \phi$$

$$d_r = \frac{2R}{1+\sqrt{5}} = \frac{R}{\phi}$$

$$d_s \frac{2R}{\sqrt{5-1}} = R.\phi$$

Hexagon : The side of the regular hexagon equals the radius of the circumscribed circle. Regular hexagon can be divided into six equilateral triangles. A star-hexagon or hexagram can be composed of two independent equilateral triangles.

If R is the side of the hexagon, its surface $S = \frac{3R^2\sqrt{3}}{2}$

Octagon : The symmetry of a regular octagon is based on square and its diagonal. Taking R as the radius of the circumscribe circle, the side of the octagon

Taking R as the radius of the circumscribe circle, the side of the octagon $o = \frac{2R}{\sqrt{2\left(2+\sqrt{2}\right)}}$ and the surface $S = 2\,o^2\,(1+\sqrt{2})$

Regular octagon had been used in many churches in Byzantine, Arab and Romanesque architecture while octagon was the decorative motif in Moslem, Arab and Indian-Mogul art and architecture.

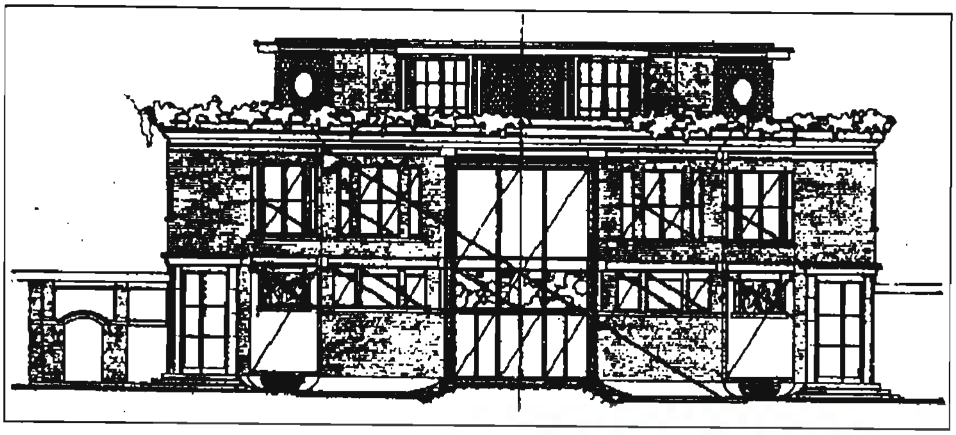
The circle found to be divided into twenty parts in Gothic designs which is further based on golden proportions. 15 sided polygons called pentadecagon were found in Gothic rosés. With these exceptions, polygons with more than ten sides are rarely found.

3.4. REGULATING LINES

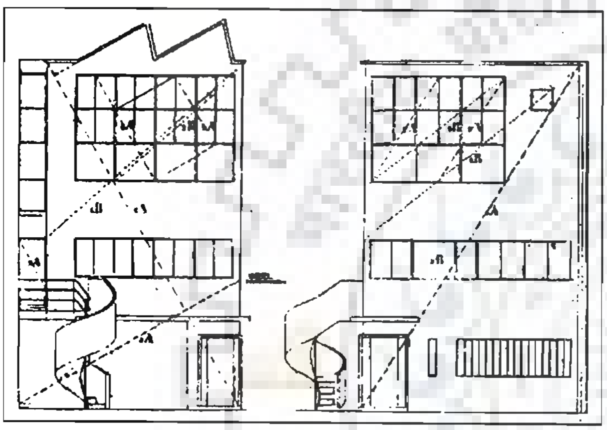
Regulating lines are the lines through which we can control the proportions and placement of elements, binding them together imparting the quality of rhythm thus resulting in overall harmonious composition. Two rectangles share similar proportions if their diagonals are either parallel or perpendicular to each other. Such diagonal as well as other lines showing common alignments of parts are called regulating lines. These therefore help imparting order to any architectural composition. As mentioned by Le-Corbusier (1927) [12], it is a guarantee against willfulness, a means towards an end. He further discusses that choice and modalities of expression given to those regulating lines are an integral part of architectural creation. These were used by great architects of different epochs in history to correct their works and order them mathematically. 'The choice of a regulating line fixes the fundamental geometry of the work; it fixes therefore, one of the "fundamental characters". The choice of the regulating line is one the decisive moments of inspiration; it is one of the vital operations of architecture' (Corbusier, 1927) [12].

In his book 'Towards A New Architecture' of 1927 [12], Corbusier discusses some of the examples where different systems of regulating lines came into play to order the buildings by fixing their major divisions and simultaneously governing the details of the parts. He gives the example of Achaemenian cupolas where 3-4-5 triangle was used to regulate the cupola right from portico to the top of the vault, in a stepwise manner. Similarly he described the faced of Notre Dame, Paris where according to him the proportions are regulated by the square and the circle.

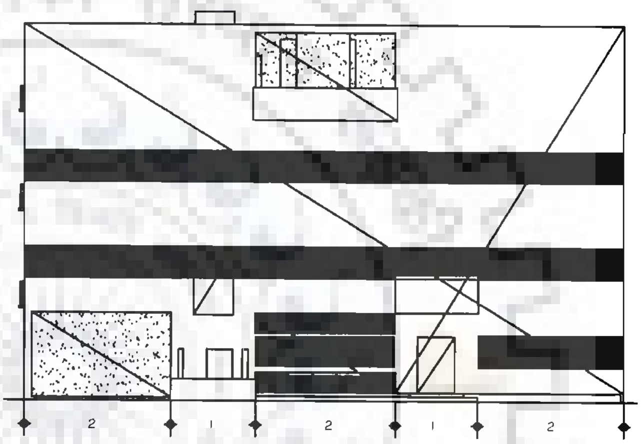
He further ascribes the judicious proportions of Michelangelo's The Capitol, Rome and Blondel's The Petit Trianon, Versailles, from the fixing of the chief divisions of the buildings to the placing and proportioning of the smaller parts, to the careful positioning of the right angle as a regulating



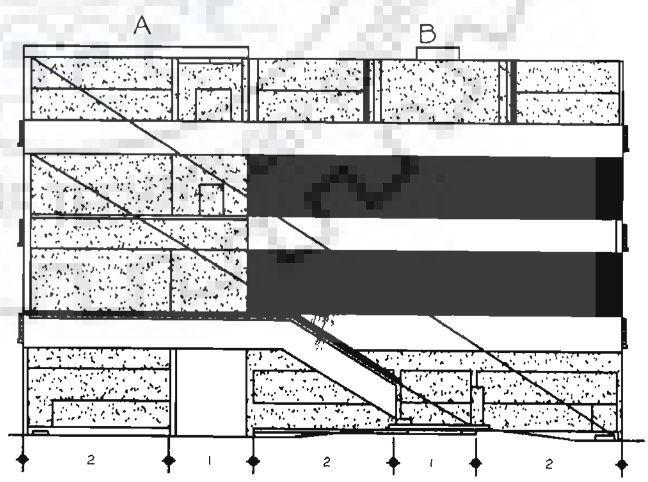
Villa 1916 , Le Corbusier



Houses By Le Corbusier



Villa Stein : Front Elevation , By Le Corbusier



Villa Stein : Rear Elevation , By Le Corbusier

Fig 3.4 COMPOSITION CONTROL THROUGH REGULATING LINES

principle. Corbusier extends his discourse regarding the application of regulating lines through the examples of his own residential buildings which he designed in 1916 and 1923 to prove its relevance in 20th century thereby claiming that the sense of monumentality and order is the result of this particular proportioning system.

3.5. MODULE-BASED PROPORTIONS

The term module is derived from the Latin word 'modulus' which means small dimension. The module is a unit of measurement set out to create internal order thereby determining the overall proportions of the building and coordinating it with various parts. It also secures dimensional coordination among different structural and non-structural components. Use of module based proportions result in economy of thought and action. The module has basically three functions:-

i). It is the basic measurement upon which architectural design is based.

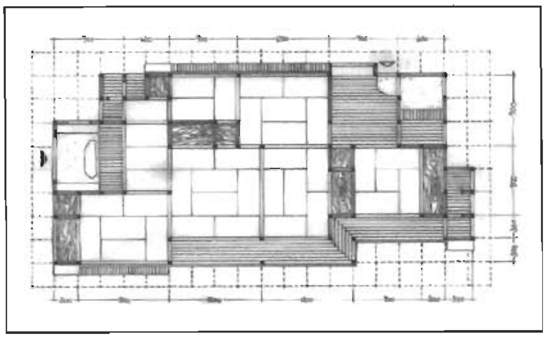
ii). It determines the exact dimensions of each of the building components as each component confirms to previously defined dimensions.

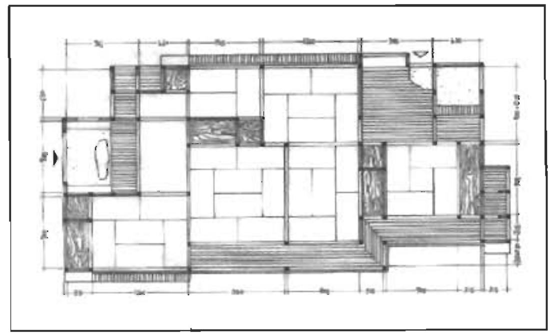
iii). It co-ordinates the shape, size and location of the component in the building. Design can be freed up by subdividing the building materials to attain a spatial coherence as necessitated by function, movement, linkages, perception of space etc.

Analysis of historical architecture establishes that the prominent architecture of the past was modular in plan and construction. The use of modular system led to simple arithmetic and geometry and standardized measure. "It is true in almost all architectures, including various traditions, that a style is defined after a successful modular system has been developed which is then formalized into a design cannon such as the classical orders" (Salingaros & Tejada, 2001) [81].

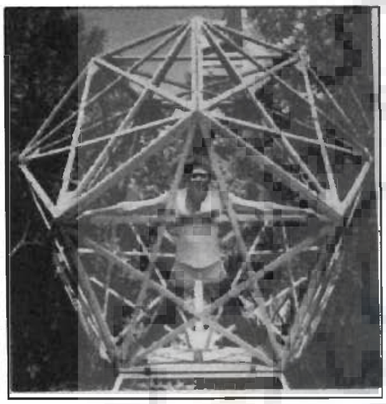
Whether it is Egyptian or Greek temples, their proportions are governed by some basic unit. In a Greek temple, it is the circular column derived from the trunk of a tree which is the basic unit of its determining the dimensions of its components. Romanesque and Gothic architecture are also characterized by large geometrical modules such as columns, bays etc which are further subdivided into internal substructures like decoration, fluting etc resulting in a visual balance created by the richness and variety due to co-existence of varied modular scales. Similarly the use of modularity to create a pattern consisting of a discrete unit arranged in a definite order forms the basis of Hindu and Islamic architecture.

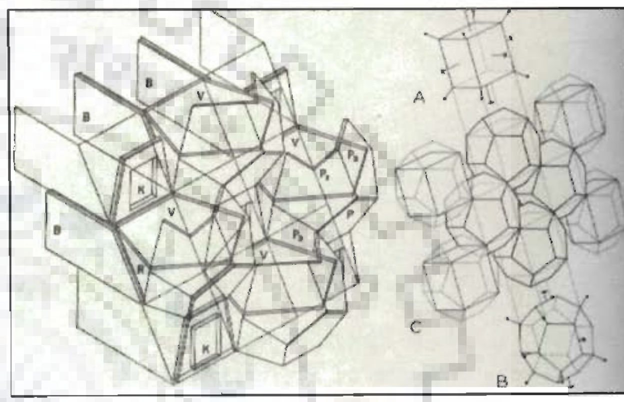
The dimensions of all the rooms in a traditional Japanese house are developed on the basis of sizes of mats which in turn are based on human dimensions. In traditional Japanese houses order was created based in the use of modular systems established to standardize some of the building parts. There were two methods of designing with modular gird - Kyo-ma method and Inaka-ma method. In the former method, the structural columns are placed on the bases of one standardized module the tatami floor mat (3.15 x 6.30 shaku or 954.5 x 1909 mm), the centre to centre column spacing (or the Ken) varied between 6.4 to 6.7 shaku according to the size of the room determined by the number of floor mats. The dimensions of tatami mat were originally fixed to accommodate two persons sitting or one person sleeping thereby bringing intimate human scale to the house. The inconsistent column spacings made it difficult to determined standard measurements between them for paneling.



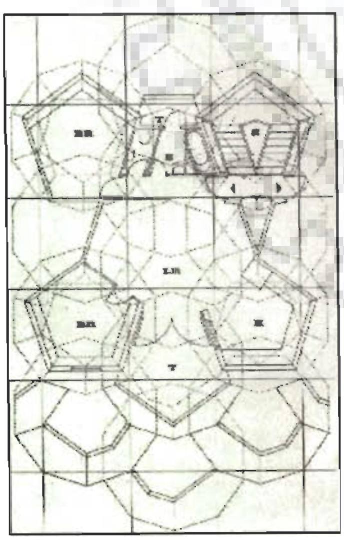


Japanese Modular System : Inaka - ma & Kyo - ma Methods of Determining Sizes of Spaces





Basic Polyhedral And Its Combination : Ramot Housing , Jerusalem By Zvi Hecker



Modular Plan & View : Ramot Housing

Nagakin Tower

Fig 3.5 MODULE BASED ARCHITECTURE

In the Inaka-ma method, the Ken grid (3 x 6 shaku or 3 x 6 feet) is the main modular determinant and the tatami mat is subordinate to it. The panels between two columns, in this case, can be standardized thus leading to greater economy of material. In this case, several standard sizes of mats can be used from which varied combinations could be derived to fit in the rooms. Comparing two houses of the same design each built under these two different modular systems, we find that in terms of square footage, spaces in the Inaka-ma method are on the average 15% smaller than those created by Kyo-ma method. The modular systems make Japanese houses "additive" in nature without any principle of hierarchy. "Because of their 1:2 modularity, the floor mats can be arranged in the number of ways for any given room size. And for each room size a different ceiling height is established according to the following:

> height of the ceiling (shaku), measured from the top of the frieze board = number of mats x 0.3" (Ching, 1996) [8].

Ken, apart from the absolute measuring unit in Inaka-ma method, became an aesthetic module in Japanese architecture for ordering the structures, materials and space.

From Vitruvius to the 'Modular' of Le-Corbusier there had been many attempts in different periods to relate the symmetry and proportions of buildings to those of human body. The measurements like inch, foot, cubit are another example of a modular series.

Modular proportions are represented graphically by means of a grid consisting of grid lines and the intervals. Grid is geometric and ordered, being repetitive it gives a regular interval to the organization of the visual image. A square grid is the simplest one. Variations on a simple grid tend to make compositions more dynamic. Directional grid can be created by changing the direction of horizontal and vertical grid lines at an angle to make more dynamic directional grid.

The final variation is the expansion grid starting from the simple grid and combining area into larger and more complex shapes without leaving any left over space between combinations.

According to Salingaros and Tejada (2001) [81], in order to create interest and variety there must be hierarchy of scales present in modular system following an inverse proportionality i.e. many smaller scales, fewer intermediate ones and very few larger ones as followed by nature in its creation.

In the reconstruction following Second World War module based systems were adopted by many countries so that building elements can be exchanged and the common market supplied. The module on which modular co-ordination is based is called the basic module (M). "International agreement in the value of basic modules of 100mm for metric countries and 4 inches for countries using imperial units were obtained in 1969 in the form of the ISO Recommendation…" (Nagarajan, 1976) [45].

The dimensions of the building components are the multiples of basic module (M). It is therefore the basis of dimensional standardization. Depending on the functions, we use:

material module

production module

transport and assembly module

sanitary module

fitting module

The integration all these modules lead to the generation of planning module which forms the basis of architectural design in contemporary mass-produced building components. Where space dividing and supporting functions coincide, the planning module and structural module becomes identical.

Kisho Kurokawa's Nakagin Capsule Tower and Watanabe's Sky Apartment are the example of the use of module- based proportions in the second half of twentieth century.

Polyhedron is the basic module in the works of Zvi-Hecker. Use of polyhedral solids from the basic to the most complex ones and compounding or transforming the structural system forms the language of his works. Of all his works, Ramot Housing at Jerusalem (1980) [71] is an outstanding example of the use of module based proportions in architecture in the later part of 20^{th} century.

3.6. PREFERRED DIMENSIONS

Nagarajan (1976) [45], in the context of standardization defines preferred dimensions as those having special property of additively or flexibility. He explains the requirements of preferred dimensions as:

i) The figure should be multiple of basic module.

ii) Each larger figure should permit division by as many figures as possible.

iii) Between figures there should be such relations that the larger figures are multiples of smaller ones and sum of two or more of these.

iv) At the lower level of the series, the distribution of the figures should be denser than higher up.

He also describes 'Modular' given by Le-Corbusier is an instrument of architectural proportions and a means of ensuring repetition of similar shapes, as a system of preferred dimensions intended for standardizing the sizes of mass-produced building components.

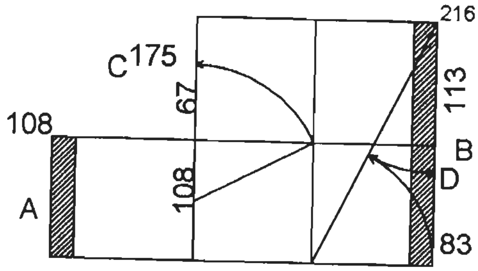
It is in this context that 'Modular' device by Le-Corbusier is discussed here as a system of architectural proportions. By the term 'preferred dimensions' here we are only concerned with 'Modular'.

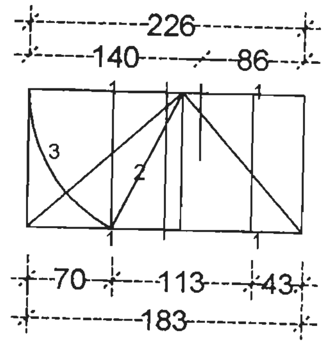
3.6.1. The Modular

Inspired by the measuring tools of ancient higher civilizations of Greece, Egypt etc. which were infinitely rich and subtle as they based on the proportions of human body, Le-Corbusier devised and published a system called 'The Modulor- A Harmonious Measure to the Human Scale Universally Applicable to Architecture and Mechanics' in 1948 [10] based on the measures of human proportions and suitable for the standardization of sizes of building components. A second volume 'Modulor II' followed in 1954 [11].

A square of 113 cm side is joined with another square of same size so that a double square is formed in the ratio 1:2. Man of height 183 cm (6 feet) is inscribed with arm upraised in this double square.

Corbusier observed that the solar plexus lies in the centre of man with arm upraised. Two golden means are introduced, one adding to the square

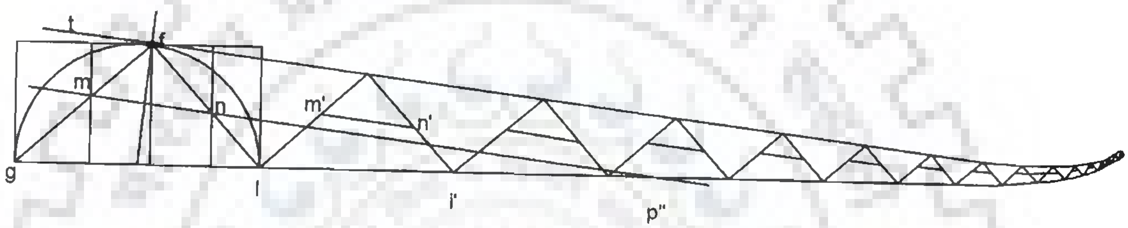




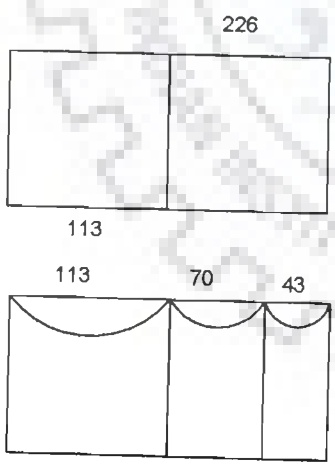
l'unite
le double
le rapport de A
le rapport de B

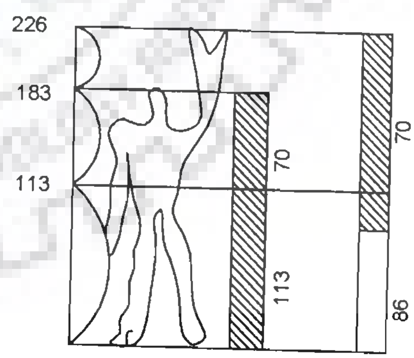
A (= 108)
B (= 216)
= C (= 175, 108+ 67)
= D (= 83, 143 + 83)

Development of Chain of Dimension
From Basic Length 113 cm : Blue Series
At Bottom Red Series Top Blue Series
Derived From 2 x 113 cm



Premier trace (1948) avec tolerence de $\frac{1}{6000}$

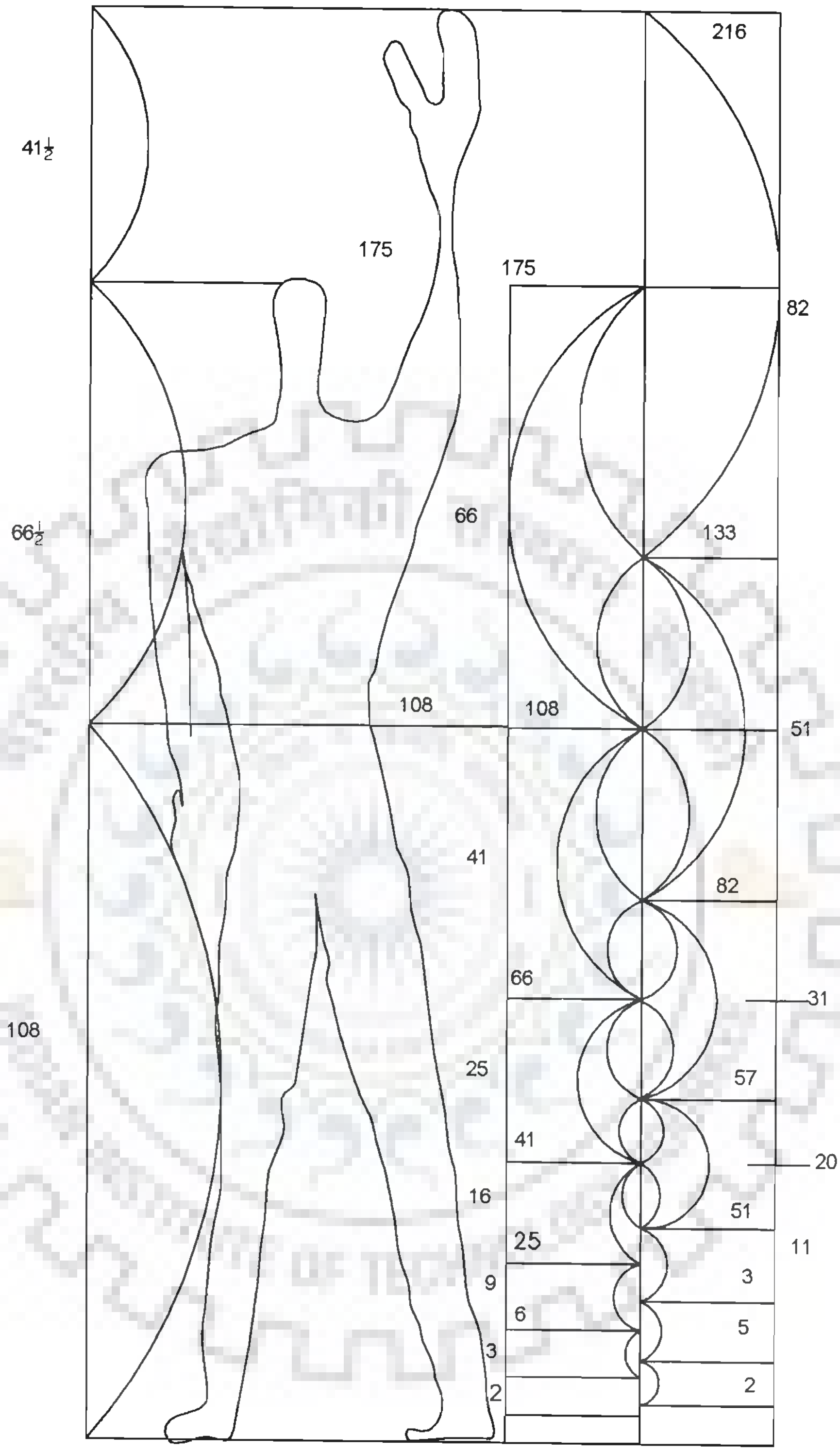




Double Square And The Golden Section

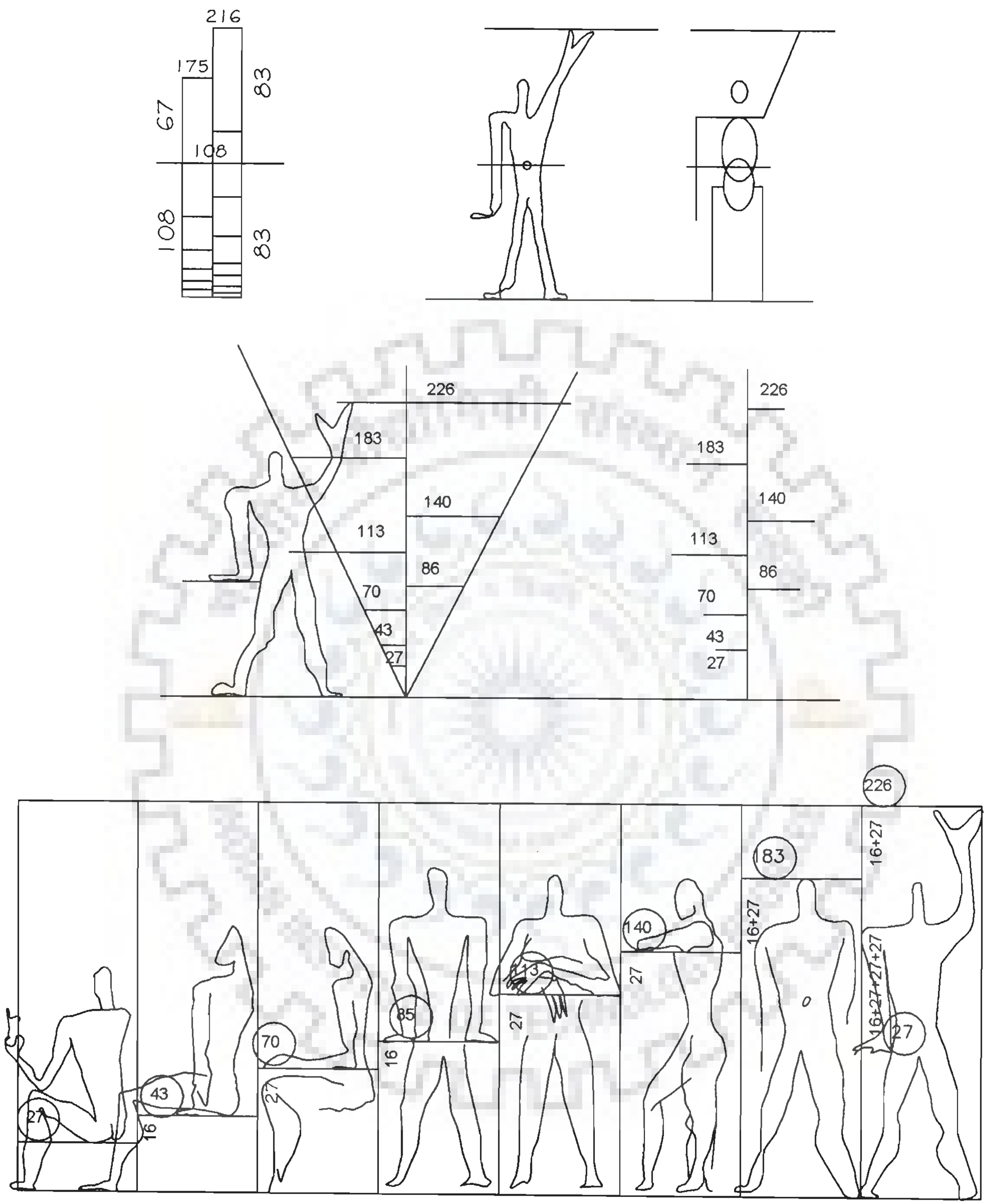
Golden Section In Relation To Human Body

Fig 3.6 (a) THE MODULAR BY LE - CORBUSIER



Relationship Between Chain of Dimension of Modular And Those of Human Body Taking Height of Body As 175 cm

Fig 3.6 (b) THE MODULAR BY LE - CORBUSIER



Charectaristic Relations of Modular Measures To The Human Body Taking Height of Body As 175 cm

Fig 3.6 (c) THE MODULAR BY LE - CORBUSIER

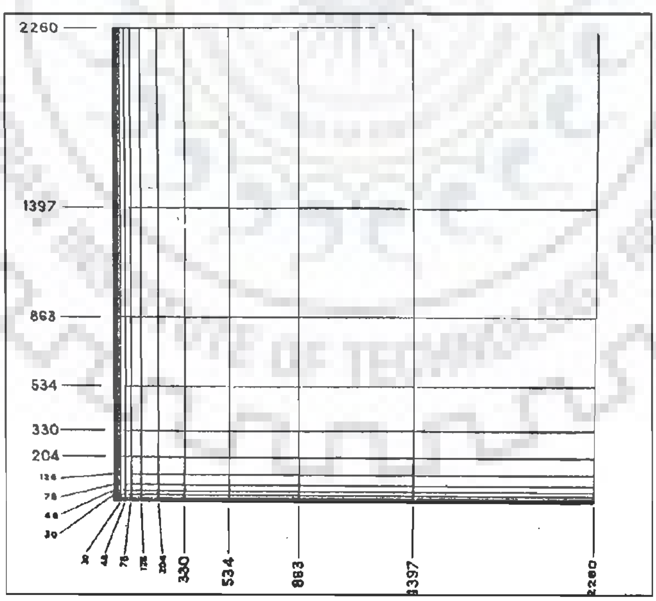
(113 + golden section of 113 i.e. 70) and another subtracting from the double square (226 - golden section of 226 i.e. 86). The first one determines the relationship between the solar plexus and from there to the head. The second establishes the relationship from foot to the fork and from fork to the tips of the fingers with arm upraised. The irrational number of the golden section can be approximated by numbers of the Fibonacci series.

In the Modular, 43, 70, 113 are in Fibonacci series originated from a single square of side 113 cm and its golden section. It forms the basis of the Red series (RO). 86, 140, 226 are also in Fibonacci series derived from double square and its golden section forming the basis of Blue series(BL). The terms of Blue series are always double to those of Red series. By interspiralling the two ϕ series Corbusier arrived at a series of terms which could be used as a system of measurements in design. Infinite number of combinations could be prepared from the terms still maintaining the human scale every where. Therefore, Modular was designed to give harmonious proportions to every thing from door handle to the dimensions of urban space. It was also intended to be used by industry to standardize building components. "The Modular was more than a tool; it was philosophical emblem of Le-Corbusier's commitment to discovering an architectural equivalent to that in natural creation" (Curtis, 1992) [16]. Small terms from the series can be fitted between any lengths generated by the two bigger terms of the series, thereby filling the gap harmoniously.

VALUES EXPRESSED IN METRES				VALUES EXPRESSED IN FEET AND INCHES	
RED SERIES: RO		BLUE SERIES: BL		RED SERIES: RO	BLUE SERIES: BL
cm.	m.	cm.	m.	inches	inches
95,280·7	959·80	117,773·5	1,177·73		
58,886·7	588·86	72,788·0	727·88		
36,394·0	363·94	44,985·5	449·85		
22,492·7	224·92	27,802·5	278·02		
13,901·3	139·01	17,182·0	171·83		
8,591·4	85·91	10,619·6	106·19		
5,309·8	53·10	6,563·3	65·63		
3,281·6	32·81	4,056·3	40·56		
2,028·2	20·28	2,500·9	25·07		
1,253·5	12·53	1,549·4	15·49		609·931" (610")
774·7	7·74	957·6	9·57	304·962" (305")	376·966" (377")
478·8	4·79	591·8	5·92	188·479" (188½")	232·984" (233")
295·9	2·96	365·8	3·66	116·491" (116½")	143·994" (144")
182·9	1·83	226·0	2·26	72·000" (72")	88·993" (89")
113·0	1·13			44·497" (44½")	
69·8	0·70	139·7	1·40	27·499" (27½")	55·000" (55")
43·2	0·43	86·3	0·86	16·996" (17")	33·992" (34")
26·7	0·26	53·4	0·53	10·503" (10½")	21·007" (21")
16·5	0·16	33·0	0·33	6·495" (6½")	12·985" (13")
10·2	0·10	20·4	0·20	4·011" (4")	8·023" (8")
6·3	0·06	12·6	0·12		
3·9	0·04	7·8	0·08		
2·4	0·02	4·8	0·04		
1·5	0·01	3·0	0·03		
0·9		1·8	0·01		
0·6		1·1			
etc.		etc.			

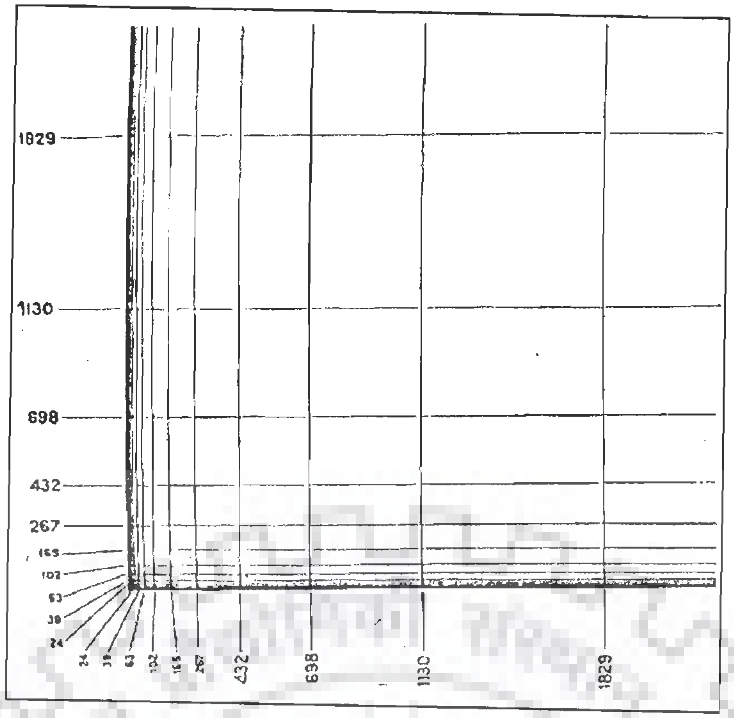
THE INCH .... 2·539 c
THE FOOT .... 30·48 cm

The Limitless Numerical Values

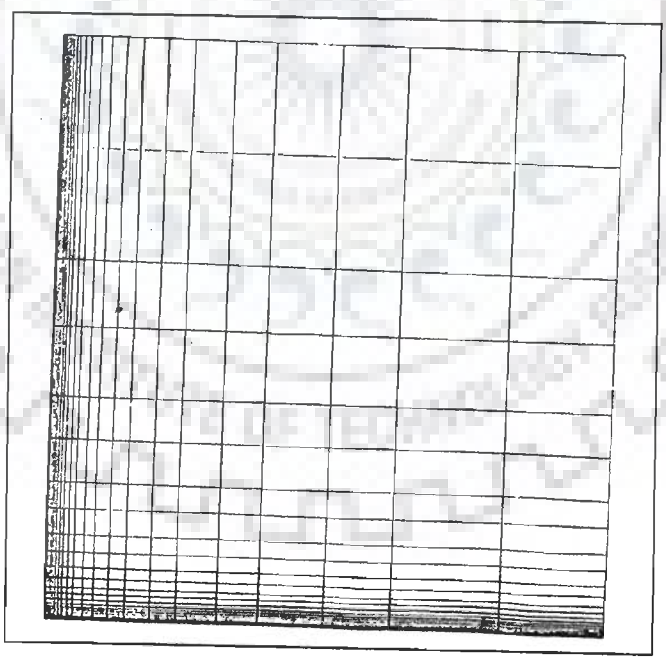


The Weave of BL (Blue Series)

Fig 3.6 (d) MODULAR WEAVES -1

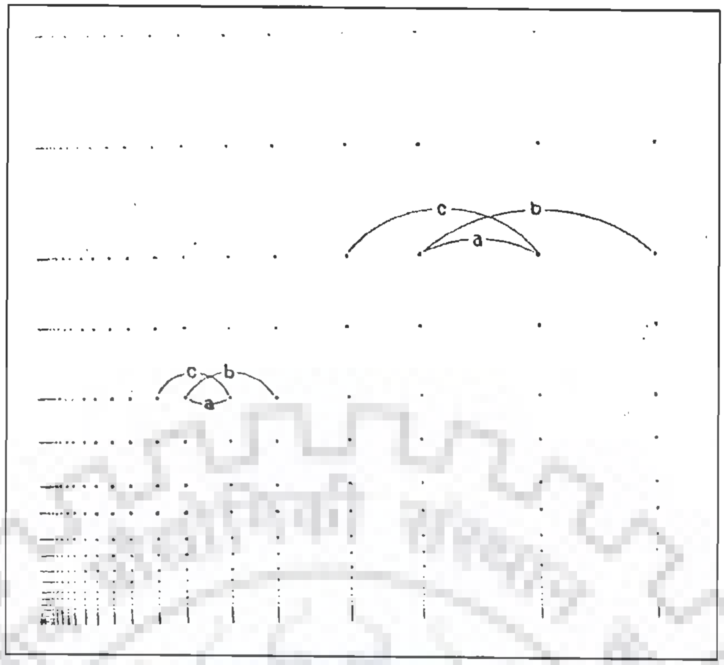


The Weave of RO (Red Series)

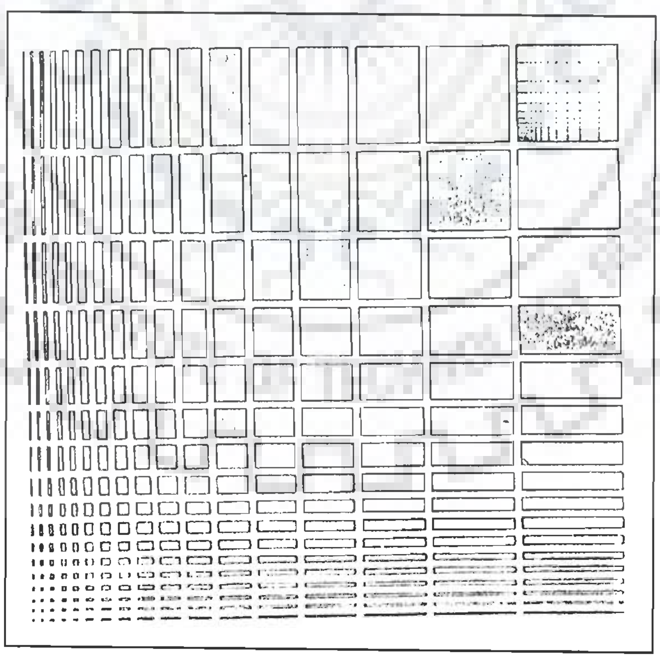


Two Weaves RO And BL Superimposed

Fig 3.6 (e) MODULAR WEAVES -2



Points of Intersection RO And BL Superimposed



The Harmonious Divisions of The Same Origin

Fig 3.6 (f) MODULAR WEAVES -3

Shown here are the weave of Red series (RO), weave of Blue series (BL) and the two weaves superimposed on each other, also shown is their point of intersection where we can read the basic values of the Golden rule namely:

(a) the initial value (unit)

(b) the double unit

(c) its Golden Section

Stevens (1990) [60], describes that when the two series are written in order, then a term of red series forms the arithmetic mean of the two blues on either side while blue forms the harmonic mean of two corresponding reds.

Red series:

…270 430 700 1130 1830 2960

$\ldots d \quad d\phi \quad d\phi^2 \quad d\phi^3 \quad d\phi^4 \quad d\phi^5$

Blue series

…540 860 1400 2260 3360 5920

$\ldots 2d \quad 2d\phi \quad 2d\phi^2 \quad 2d\phi^3 \quad 2d\phi^4 \quad 2d\phi^5$

Writing them in order, we get:

430 540 700 860 1130 1400 1840 2260 2960 3360

Where 1130 (red) is the arithmetic mean of 860 and 1400 and 1400 (blue) is the harmonic mean of 1130 and 1830.

The terms of interspiralling series follow each other into unbroken progression with no upper of lower limits. However, there are diverse criticisms attached to this proportioning system.

CHAPTER 4

GEOMETRY AS THE BASIS OF ARCHITECTURE

4.0. INTRODUCTION

The role of geometry in architecture, as reviewed in previous chapters, is to form a meaningful domain for man where he is psychologically and physically comfortable – a defined place where he is in a position to relate himself, exercise his control, simultaneously interacting with the surroundings and at an upper level feel himself a part of higher reality. This chapter, thus, deals with the role of geometry as an organizational tool in architecture by analyzing its relationship with various intangible and tangible aspects which are comprehensively responsible in the making of architecture; holistic in nature i.e. it seeks the relationship of geometry with aspects like symbolic and visual references, form, space, circulation, articulation and structure. It aims at framing an overall view regarding contribution of geometry in architecture without going into much detail in any of the aspects which in itself is an extensive research work. Further investigation carried out as a part of this research work is based on the theory discussed in this chapter.

4.1. GEOMETRY AS SYMBOLIC AND VISUAL REFERENCES

According to Frutiger (1989) [22], symbolic content is the indefinable capacity of a representation to make a statement. The more comprehensively the symbolic content is expressed in the represented work through aesthetic perfection, the more symbolic value it commands and becomes more worthy of worship. The symbolic element is a mediator between recognized reality and the mystic invisible realm of religious, philosophical, spiritual, magical beliefs.

The symbolic element is also a strong vehicle to represent the visible realm of power and authority. It extends from a conscious reality to the field of unconscious ideal. The patterns, designs and structures of innumerable varied sizes found in nature are symbolic of the underlying metaphysical principles of interconnectedness, inseparability of relationship between part and the whole, continuously reminding us of our relationship to the whole - the idea which forms the genesis of all metaphysical foundations in mind.

Man has an innate feeling for geometry. "The 'visible' part of a geometrical sign consists of a more or less complex assembly of straight and curved lines, whereas the 'invisible' part consists of the mathematical laws under which the lines are oriented, extended and turned. The projection of any kind of symbolic meaning comes from this aspect of the sign, which we might call its metaphysical content" (Frutiger, 1989) [22].

Sacred geometry in architecture is very rich in symbolic content. The practice of geometry in sacred buildings is an essential technique for self-development, harmonizing matter and spirit. The application of such geometry is for the transformation of ideal into the mundane thereby providing an empirical method for solving philosophical and moral issues. Sacred geometry is thus the means to the goal. It relates to the study and application of particular proportions and geometrical figures in both time and space. The ϕ ratio, musical scaling, the square root numbers, regular geometrical figures, the logarithmic spiral are few of the elements of symbolic geometry. Because of the strong symbolic content primary geometric shapes are found in the architecture of exceptional importance. Different religions have different mythological beliefs and images to relate religion with geometry. The beliefs give visual perceptions and create geometry of the building. Each of the geometric elements is impregnated with definite symbolism thereby transforming the intangible and abstract ideas of religion's philosophy into physical and comprehensive form easily appreciable by people bridging the gap between religion and people.

However, the use of primary shapes like square, triangle and circle are found in different regions of the earth in varied cultures at widely different times expressing similar meanings. Following is the description of commonly used geometrical figures and proportions from symbolic reference.

Square: It implies earth's surface in the pre-historic sense, at the same time indicates the four points of compass. The four corners in Chinese symbolism mean the outmost points of earth. Square is static & neutral in character because of equal dimensions of all sides. It represents the pure and the rational. Square also symbolizes creation in matter. Its three-dimensional form cube inherits the quality of square; define the three directions of three dimensional reality. The square and cube also represent the physical manifestation unevolved.

Triangle : If all the three sides of a triangle have same angles, it is called equilibrium triangle. The triangle with horizontal base represents stability and permanence. When the triangle is reversed, standing on its vertex, it becomes active & unstable in character and be balanced in a precarious state of equilibrium. It is regarded as an icon of ineffable oneness, the indivisible fulfillment of the universe.

Circle : The line of circumference has the character of eternal recurrence neither beginning nor end but having a defined centre. It is the most simple & regular shape. This is associated with the idea of cyclic recurrences, the course of time coming from no where with no end. It has strong symbolic content because of its association with sun, moon and stars. The circle is also a symbol of movement since the invention of the wheel. It is stable and self centering in its environment.

When inside the circle, facing centre, the impulse is towards centre or a search for a mysterious concept of life. While facing opposite, an active life radiates from centre outwards. Standing outside the circle resembles with sun & moon with beams radiating from circular form.

The ratio of circumference of circle to its diameter, Pi, (= 3.1415926..) is an irrational number and cannot be represented in terms of ratio of two whole numbers, thus symbolizing that the essence of the circle exists in a dimension which transcends the linear rationality that is contains. Square and circle are the symbols of perfection in all respects in all the civilizations.

Sphere, of which the circle is a two dimensional shadow is the simplest of forms with an expression of completeness, integrity and unity. All points on the surface have equal importance, equally distant from the centre. As mentioned by Bruce Rawles, atoms, cells, planets and star-system all echo the spherical realm of acceptance, simultaneous potential and fruition, the microcosm and the macrocosm.

Pentagon : It is formed by placing five points equally spaced on the circumference of the circle within which lies the pentagram or five pointed star. The proportional relationship of the diagonal of a pentagon with its side is ϕ. Its symbolic content gets intensified because of this ϕ proportion.

Doczi (1998), describes the pentagonal star as the sacred emblem of the Pythagorean fellowship where men and women live in communities and abstaining from all luxuries dedication to the life of moderation and practice of healing. The five stars is a universal symbol of good portent appearing in the national flags of many countries. The pentagon and pentagram are frequently found in plant patterns therefore manifesting the potential of harmony hidden within the world of matter.

Hexagon : It is the expression of symmetry and balance. All the diagonals pass through the centre of the circle in which hexagon is inscribed. Within it lies the hexagram, the six-pointed star. This hexagram is composed of two superimposed equilateral triangles in opposite directions. According to Bruce Rawles, the trinity has replicated itself in the world of matter as represented by the inverted triangle.

The relation between God and His creations in matter can be seen in Vesica Piscis formed by the half overlapping of two circles. Vesica is the geometric basis of making the hexagram so a connection exists between these two symbols. Vesica represents two aspects of God masculine and feminine. The two circles apart describe separation while their overlap determines harmony through the blending of masculine and feminine qualities.

The Square Root of Two : It is the dimension of hypotenuse from the conjugal union of horizontal and vertical. It represents synthesis, growth reconciliation of polarities by considering equally both the perspectives. It is originated from square and being irrational in character represents unity, a higher expression of truth.

The Golden Ratio : It is also called as ϕ ratio / sacred cut / golden mean / divine proportion. It is found to be present every where in every aspect of the universe so termed by Renaissance artists as divine proportion. It symbolically links the new generation with its ancestors maintaining the continuity of relationship to retract its lineage. In Pythagorean School, The ratios of segments in a pentagram were regarded as sacred as they are in ϕ relationship.

It is regarded as aesthetically most pleasing proportion and therefore used by many artists and architects since pre-historic times. It is generally found to exist in those artifacts where intuitive and reasoning faculties of man are integrated at their best. Its use creates an optimal effect of beauty, balance and harmony.

Frutiger (1989) [22], describes that human body cannot convey any symbolic content on its own and the symbolic element enters only in connection with a given object or creature. Human body has been considered to be the most perfect in the hierarchy of creatures by different artists in all the cultures in the human history. It was considered to be the image of perfect harmony prevalent in the universe and therefore had been subjected many times to geometrical and proportional analysis in all the cultures. Drawings of human body have always been used as yardsticks for standards for participation in the cosmic harmony as well as for the construction of mythological, philosophical and religions world-views.

Symmetry and hierarchy in architectural compositions are important principles associated with symbolic and visual content of a building. Perfect symmetry is generally imparted in compositions representing higher reality where nothing could be added or subtracted but for the worse. The type of symmetry used depended on the philosophical ideal of the architecture. Romans employed axial symmetry, while Christian architecture up to Gothic period exercised bilateral symmetry, rotational and reflectional symmetry can be witnessed during Renaissance.

In axial symmetry the arrangement of architectural elements is such that like elements are always opposite to each other giving rise to monumental and static spaces; bilateral symmetry is the most common one where halves of the composition mirror each other, the axis at symmetry assume symbolic role by becoming path symbolizing earthly pilgrimage of man from mundane to God. While reflection lays emphasis on the center because man assumes the central place, being God's most important creation of the cosmos and the sacred building is an image of the same.

Hierarchical differences reflect the degree of importance attached to forms, spaces and the symbolic role they share in the organization. The manner in which these symbolic differences are revealed in the form establishes visible hierarchical order.

The use of golden proportions has been claimed by researchers in stonehenges of Neolithic period. These stonehenges were considered to be of astronomical and ritual importance. Greeks symbolized God in the image of human being and their architecture reflected the human proportions in the Orders, along with the use of golden proportions as a dynamic principle of philosophy and wisdom. The Greek volumes were organized axially. Romans created monumental and static spaces in their buildings. The use of regular circular form to create exceptional quality immersed with the symbolism of cosmos can be experienced in great building of Pantheon. Apart from that the use of golden section for aesthetical purposes can be seen in public buildings like Colosseum etc. The definition of path and goal formed the basis of Christian architecture. The plans were organized in cross shape symbolizing Christ crucified. The emblem of cross was elaborated as unfolded cube.

In Renaissance architecture, the spatial geometry was created by additions of various smaller units according to their hierarchical disposition. Circle was the most perfect and divine form reserved for churches and public buildings. The elements like centre, circle and dome were used for experiencing cosmic harmony. The static ideal image of renaissance was changed into dynamic pulsating quality during Baroque period by creating infinite continuity in relationships among the parts of the buildings and by the creation of visual perception of continuity between inside lower spaces rising to merge with the sky above as can be seen in the Church of S. Ivo Della Sapienza.

Hindu architecture of temples and stupas represents their own concept of cosmology different from the western world. Square and circle geometry were used in the development of temple form. Vastu-Shastra concepts are employed to create architecture in harmony with cosmos.

Vastu Purusha Mandala is an image of laws governing cosmos. It is generally square in plan but may have triangular, circular, hexagon shape also. Here centre is the most important place around which concentric rings of the shape of mandala are drawn. In Hinduism, and Buddhism as well centre is the place where soul experiences salvation. All geometrical truths in their varied form are arranged according to this importance attached to the centre. It represents world–axis connecting heaven and earth. Even the whole cities were sometimes planned in the shape of mandala consisting of concentric squares.

Axis, symmetry and geometry form the basic principles of Islamic architecture. Geometry is used for organizational and aesthetic purposes. The intention of its use is to seek unity with God through the application of geometrical figures imbued with sacred meanings.

The symbolism inherent in geometry started getting transformed during sixteenth century and this change continued till twentieth century, with the changing concepts of universe. The scientific outlook resulted in new ideas of freedom as opposed to conventions and traditions.

Functionalism was propagated in the first half of the twentieth century with 'form follows function' as its basic dictum. This led to the creation of architecture universal and rational in nature. Le-Corbusier attempted to develop purist aesthetics suitable to the universal nature of architecture. The next generation decided to impart identity to architecture by looking back into the realm of symbolism and regional characterization. Contemporary architects are exploring and experimenting new domains in architecture, thereby attempting to create symbolic vocabulary suitable for the contemporary architecture by the powerful application of geometry.

Geometry is applied to create symbolic and visual references which can be categorized into following four types:

Timelessness : In this case, symbolism is used to express the laws / beliefs considered to be eternal in nature. Such symbolic contents are generally used to represent religion, philosophical and spiritual beliefs of any civilization. In the past, different cultures manifested their beliefs, world -views, in architecture through varied symbolism.

Visual : The main emphasis here is the generation of order and creating superior aesthetic quality in the architectural composition through the application of geometry.

Function : The purpose of geometry in this case is to create functionally efficient architecture including anthropometric and ergonomic dimensions.

Time-Boundedness : In this case, geometry is mainly used to create architectural form which represents ideas or beliefs held by major proponents of specific time period. Through the symbolism used in the building, we can categorize it in terms of architectural 'isms'. For example, the ideas of Post-Modernism, Deconstructivism etc. are categorized here as time bounded concepts.

4.2. GEOMETRY AS FORM

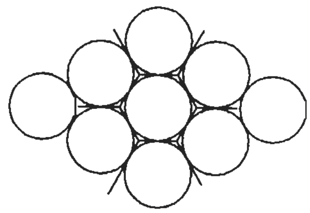
"The Ultimate object of design is form" (Alexandra, 1970) [2].

It is well known fact that there is regularity in the world of Nature around us. Ordered mathematical information generates positive emotional responses. Certain regularity as a technical necessity is essential to fulfill the physical and psychological requirements of human beings. "The demands of rationality, compactness of the grouping of spaces, and structural integrity make geometry a prime necessity to discipline architectural design" (Meiss, 1990) [42]. Simple geometrical figures known to us are helpful to fulfill such requirements. Circles, squares, triangles, spheres, pyramids, cones etc are the figures into which we simplify the complex world around us in order to understand and identify the places. As mentioned by Unwin (1999) [64], geometries emerge from our dealing with the world, geometry can be derived from an attitude of acceptance and it can also be associated with the attitude of control. While the former can be linked with our learning from the geometrical forms inherent in Nature the other can be associated to impose regularity and order in the built environment. Research shows us that the geometrical forms and proportions which architects and artists imposed in their compositions for regularity and order are the same which they have learnt over a passage of time from the very understanding of natural laws. It is necessary to have a short glance over the forms of Nature."... in some cases at least, the forms of living things can be explained by physical considerations and to realize that in general no organic form exists save as are in conformity with physical or mathematical laws" (Thompson, 1975) [63]. Nature manifests its discipline in the form of certain limited geometrical forms and proportions which are incorporated by man to take part in the harmony of the cosmos. Thompson (1975) [63], discusses that in liquids whether in motion or rest, the ultimate form which it attains is symmetry and regularity. The small parts 'cells' ultimately form hexagonal prisms of equal dimensions having fixed cell-size depending on many factors. The hexagonal conformations, witnessed in the cells of bird bee, are also the result of many physical factors and necessities. In the case of animals consider the group of microscopic organisms called Radiolaria rich in diverse species. The radiolarian skeletons complex and delicate, in spite of their minuteness and simplicity of the 'unicellular' organisms within which they grow, witness wonderful appearance of geometrically regular forms. Observing plants like snow-flakes, the thin hexagonal plate or prism with co-equal angle of 120^0 is the underlying mathematical form to which Nature adds its own richness and beauty by the combination of similar plates with identical angles and varying lengths repeated in unusual symmetry.

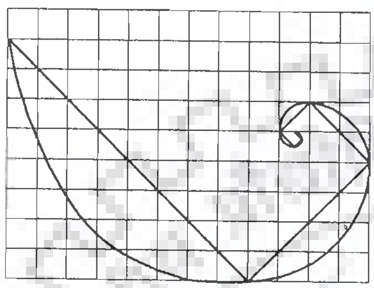
Thompson (1975) [63], further discusses that no system of hexagons equal or unequal, regular or irregular can completely enclose a space and there must be certain number of faces other them hexagons in the form of squares or pentagons. This is how Nature adds variety to its basic theme.

Thompson (1975) [63], further expounds upon some species among vast variety of Radiolaria whose skeletons consist of radiating spicular rods of fixed number and position, having interconnecting rods or plates, tangential to the more or less spherical body of the organism. The forms of the species resemble the geometrical polyhedral solids, in one case a regular octahedron, in another a regular or pentagonal dodecahedron and in third a regular icosahedron. The forms appear to be symmetrical from all the sides though in all cases the facts are not plane surfaces. The radial spicules are at the corners, accordingly, six in octahedron, twenty in dodecahedron and twelve in icosahedron. Thompson relates these polyhedral solids with the Platonic bodies known to the mathematicians. In all these polyhedral shells, the surface is formed of minute hexagonal network.

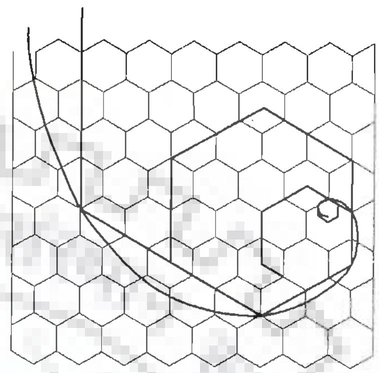
Thompson (1975) [63], emphasizes that the organic growth takes place in the form of equiangular spiral. Mathematically, equiangular spiral is the path described by a point while moving along the radius vector with a velocity



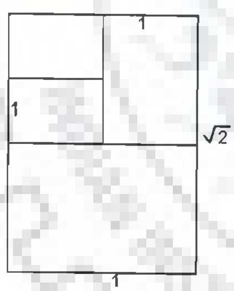
Hexagonal Symmetry - Diagram of Hexagonal Cells After Bonanni (Thompson , 1975)



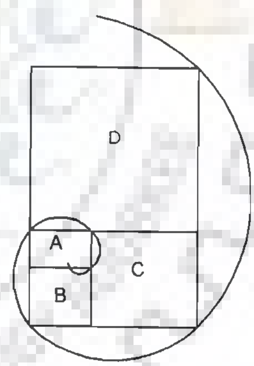
logarithimic spiral derived from
corresponding points in a system
of squares



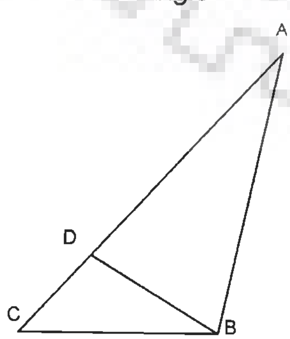
The Same Into A System of Hexagons From Naber (Thompson 1975)

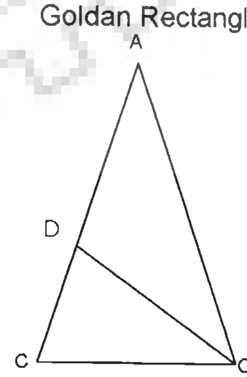


1 :√‾ 2 Rectangle



Goldan Rectangle





Triangles

GNOMONIC FIGURES (Thompson , 1975)

Fig 4.1 GEOMETRY AS FORM

increasing as its distance from the origin increase. "Each whorl which the radius vector intersects will be broader than its predecessor in a definite ratio; the radius vector will increase in length in geometrical progression as it sweeps through successive equal angles and the equation of the spiral will be $r = a^{\theta}$" (Thompson, 1975) [63]. Equiangular spiral is also called logarithmic spiral. The continual similarity of the curve i.e. the figure which grows without changing its shape is the specific property of equiangular spiral; it is this property which relates with the organic growth as each increment is similar to its predecessor and to the whole.

Gnomons : Hero of Alexandria defines gnomon as any figure which being added to any figure whatsoever leaves the resultant figure similar to the original. Gnomons can be in numbers or geometrical forms for example the square numbers 1, 4,9,16 have their successive odd numbers as gnomons:

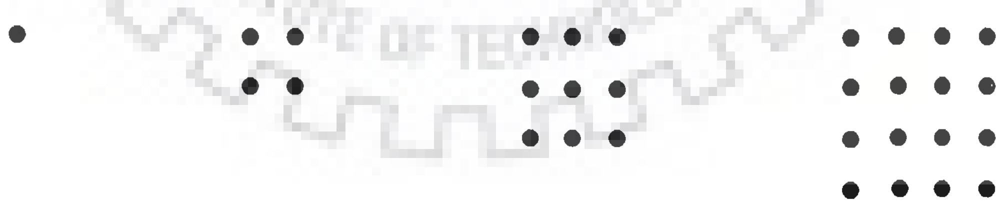
$0 + 1 = 1^2$

$1^2 + 3 = 2^2$

$2^2 + 5 = 3^2$

etc.......

representing them graphically it makes



which means the square shape remains intact with each increment. The geometrical figures such as in the rectangle of a ratio $1:\sqrt{2}$, it is clear that by doubling it or by halving it we get the resultant figure bearing the some ratio and hence is a gnomon to the previous one. The gnomons of a figure in golden ratio i.e. 1: $\frac{1}{2}(\sqrt{5}-1)$ is also obvious.

In triangles also one part is a gnomon to its other part. Equiangular spirals can be traced through the corresponding points in the gnomonic figures. Whenever a space is filled with equal and similar figures, a series of equiangular spirals is also discovered in their successive multiples. If the growth of successive parts, similar in form, magnified in geometric progression and similarly situated in form, magnified in geometric progression and similarly situated in relations to the centre of the similitude, equiangular spirals can be traced.

Different authors like Matila Ghyka (1977) [31], Rob Krier (1988), Gorgi Doczi (1994) [17], analyzed in their books how gnomonic forms & specially the golden proportion occur extensively in the plant and animal world in enriching & beautiful way.

In architecture, the term 'Form' means formal qualities of any composition i.e. the way the elements and parts are arranged and coordinated in order to produce coherent image of the whole. Form deals with both the internal organization and external profile of a building and the principle that binds the different elements.

The circle, the triangle and the square are the three most significant primary shapes. These shapes had definite symbolism attached to them during all the civilizations in history. These primary shapes when extended or rotated generate distinct regular and recognizable volumetric forms. Sphere, cube cone, pyramid, cylinder are the primary solids resulting from primary shapes.

Regular Forms : They are characterized by their orderly and consistent relationship to one another. These forms are stable and symmetrical about one or more axes. The primary solids and the platonic solids are the examples of regular forms. Ching (1996) [8], describes the various characteristics of different types of forms in his discourse. He mentions that even if the form is transformed dimensionally or by addition or subtraction of elements it can still maintain its regularity. Regular forms still maintain their identities if portion of their volumes are taken away without deteriorating their corners, edge and the overall profile.

Subtractive Forms : The building may consist of one strongly describable geometric form or a combination of more than one basic forms combined in a perceivably unified when some portion or elements are removed from the basic regular form and they still maintain their identity as incomplete wholes, they are termed as subtractive forms. If the removed portion alters the profile of the original form, it will result in ambiguity. Le-Corbusier, however, favors subtractive forms as according to him, they are generous because they are functionally satisfying and desirable architectural expression can be given to be exterior.

Additive Forms : When we add one or more subsidiary forms to the original volume, additive form results. It is the quality of a good additive form that visually the combination of the various elements should be related in a coherent manner resulting a unified composition. This can be achieved when the different elements combined so as to grow and merge with other forms. An additive form may be dominated by parts; the different elements can be combined in a variety of ways to create an overall centralized, linear, radial, clustered or grid combinations. The concept of additive and subtractive organization can be used even in the designing of smaller parts of a building. Two or more forms can overlap to create a third form which can be either simple or complex. The individual forms may subvert their individual identities or they may retain them sharing the interlocking portion.

Centralized Forms : These are characterized by visually dominating, geometrically regular form located in the center. Centralized forms are visually and functionally centripetal in nature. These can be free standing structures arising out of a context creating a strong hierarchy in the built form. They may dominate a point or occupy the center of a defined form.

Linear Forms : These can be identified with a strong sense of direction. This can be created by a proportional change in the dimensions of a form or by a repetitive arrangement of similar or dissimilar elements organized along a defined axis. Linear forms may be curvilinear according to the physical features of the site. Linear form at a place can be treated as an organizing element to which secondary forms can be attached.

Radial Forms : Radial forms are defined by the forms whose linear arms extend outwards from a centrally located element called core. They combine the characteristics of centrality and linearity. The central core may be in usually dominating or subservient to the radiating arms depending upon the nature and function of the buildings.

Clustered Forms : Different forms come together to make an organization while maintaining their individuality in most of the cases. The clustered organization may be non-hierarchical in nature representing the democratic set of values or may be attachments to a major form. Clustered forms are more flexible in nature, their volumes may interlock with each other or they may be simply in proximity with each other depending upon their function. These are visually coherent in nature as can be witnessed in most of the vernacular housing.

Grid Forms : Generally a grid is defined as a system of intersecting regularly spaced parallel lines. These lines are non-hierarchal in nature and can be extendable in all the directions. Depending upon the kind of function attached with these lines, its parts assume hierarchy. The most common grid is based on the square divisions between the intersecting lines. These forms are characterized by flexibility, repetition and bilateral symmetry providing a modular framework for internal and external organizations. Grid had been a preferred system of organization in all the cultures. It eventually represents man-made order imposed over nature exemplifying the controlled environment.

How different forms are integrated with each other giving visually and functionally desired results can be learnt from history. The design of a mosque is based on combination of square and circle. Hindu sacred architecture is predominantly governed by geometry based on square. Pantheon, Rome is an example of harmonious disposition of circle and rectangle. This rectangle is composed of two squares. The medieval and gothic architecture is dominated by centralized forms. Renaissance exemplifies additive geometry where individual units retain their identity while participating in the entire composition. These forms were determined by functions. In exclusively centralized forms, religious symbolism was the deciding factor.

Clean lines of renaissance geometry was converted into irregular form, intertwining spirals, parabolas, ovals, rhomboids etc. in Baroque period.

Industrialization transformed the nature of human creativity. The static forms gave way to dynamic ones. Russian constructivists wanted to invent forms suitable to give new shape to new society. The elementary forms were discovered to do this needful as they were considered to be the symbols of purity. Gropius' Bauhaus also laid stress on the study and use of abstract forms. Architecture was believed to be a large – scale abstract sculpture.

Corbusier's movement 'Purism' also had the same basis of seeking order and clarity in architecture through the use of pure forms. His idea of platonic solids infused with the sense of mechanization and modernism was very influential. Many contemporary architects actively pursuing research into the nature of architectural form are trying to redefine it by stripping off the conventional associations attached with form and exploring new dimensions of it which they believe are necessary for rich and varied built environment.

4.3. GEOMETRY AS SPACE

Architectural space is the thing existing between surfaces and is therefore always finite in nature. Architectural space as some thing enclosed is the product of perception and measurement. The geometry of the individual space, its relationship with the enclosure and with the surrounding spaces and forms establishes its' function. "... it can be said that it is the space between the walls, windows and pillars that determine quality. The noblest marble can hardly bring beauty to carelessly proportioned space, while rough wooden beams may well enclose outstandingly comfortable arrangement of space. 'Art does not lie in the materials but in the spaces in between,'...Well used material is often an aid to finding the correct proportions for the space concerned."(Frutiger, 1989) [22].

Primary shapes, strongly perceptible and measurable are found in the architecture of exceptional importance.

According to Meiss (1990) [42], spatial geometry can be analyzed from two points:

i) The spatial characteristic of elementary geometrical figures like, square, circle, triangle, cube, prism etc.

ii) The major forms of spatial organization for grouping different spaces.

Spatial characteristics of elementary geometrical figures:

Square : The corners, periphery, diagonals, medians and center are the defining elements of a square. Well defined corners reinforce the primary shape; the internal subdivisions of this space also tend to follow the primary shape while weak corners make the basic shape less intelligible. In both the cases the theme of centrality is emphasized in the former case through centripetally while in the latter through centrifugally. The three dimensional forms of this shape are cube, tetrahedron or prism. The principles of the two dimensions are also applicable in these forms. We transform this basic square space while designing to suit our specific requirements most of the times because of which it looses its emphasizes of centrality.

Circle : In the case of circle, the center and circumference acquire importance. The three-dimensional form of circle is found in cylinder and sphere which also reinforce the center and object character, seen from outside. Transformation of the circular space is essential in order to make it functional for everyday life in which case like square it losses its centrality and compactness.

The buildings are never square or circular because of their function; these configurations are elegantly incorporated along with function. Both these shapes have universal dimensions and are reserved for exceptional buildings of public significance. Transforming them for functional requirements means to abandon their monumental character.

Compactness and centrality are the common features of both square and the circle which makes their combination suitable for buildings of higher order incorporating the transitional figure – Octagon.

Triangle : The triangle on the other hand is an extremely closed shape because of acute angles and is less centralizing because of no precise reference to the center; however centrality can be emphasized in a triangular space by opening the middles of the three walls. Eliminating or weakening the angles result in the loss of identity of this shape, the implied figure resembles with hexagon. The three dimensional form of this space establishes important relationship between center and periphery, while transformation establishes relationships between front, backs and sides. Because of acute angles, the triangular space is not very functional unless transformed.

The qualities of rhythm, additive, subtractive or other transformation make specific kind of space for specific function through the interplay of geometry. Plan geometry controls the space sequence of a building, imparts hierarchy to them and defines particular spaces. The space organization is related to form and scale. "The form and enclosure of each space in a building either determines or is determined by the form of the spaces around it" (Ching, 1996) [8].

Ching (1996) discusses different kinds of spatial relationships as discussed here:

FORMS OF SPATIAL RELATIONSHIPS

Space Within a Space : A small space can be enveloped inside a large space in which case the smaller contained space depends on the enclosing volume for its relationship to the exterior environment. There must be clear differentiation of size of both the spaces in order to perceive this relationship effectively. The contained space may share the similar shape of the enveloping space but may or may not share the same orientation. The different orientation of the contained space creates a separate grid and dynamic residual spaces in the larger space.

The contained space may have different form from the enveloping one, this contrast in geometry may be done to emphasize and strengthen the image of the contained space

Interlocking Spaces : Two different spaces may overlap to create a common or shared space. In this case both the spaces maintain their individuality and definition. The interlocking portion of the two volumes can be shared equally or can merge with one of them becoming its integral part or can serve as a common link to both the original spaces thereby maintaining its own identity.

Adjacent Spaces : In this relationship, each space can be dealt with independently owing to its functional or other kind of requirements. The nature of the common binding space determines the degree of visual and spatial continuity between two adjacent spaces. The separating plane may limit the degree of continuity thus maintaining the individuality of each space or this plane may be highly porous as required by the circumstances.

Spaces Linked By a Common Space : In this case, instead of separating plane, between two spaces there may be a common space between two spaces placed at a distance from each other. Here also the nature of the intermediate space determines the visual and spatial relationships between the two spaces.

SPATIAL ORGANIZATIONS

As discussed by Ching (1996) [8], choice of spatial organization depends upon the functional and dimensional requirements, hierarchy of spaces, the exterior conditions etc. Five types of spatial organizations are discussed:

Centralized Organizations : A central large dominant space around which number of secondary spaces are grouped. The central space is generally regular non directional in nature. The overall organization may or may not be geometrically regular and symmetrical about two or more axes.

Linear Organizations : Here spaces are organized in a series, they may be directly related to each other or linked thro' a common linear space. These organizations may result from single oblong spaces or may consist of a series of repetitive spaces alike in size, form and function. Important spaces can occur any where in this organization. These are flexible & respond easily to the site conditions.

Radial Organizations : These are combinations of centralized and linear organizations. The linear arms may be similar to one another maintaining overall regularity of form. In pinwheel pattern, the linear arms extend from the sides of the square or rectangular central space.

Clustered Organizations : These consist of similar or dissimilar units of spaces related to one another by close proximity or visual ordering device. As these do not originate from rigid geometry, these are flexible in growth and change.

Grid Organizations : In these organizations different spaces are positioned and regulated by a three–dimensional grid pattern. Repetitive modular units of space can be set in a grid pattern. These organizations have additive, subtractive, layering and rhythmic qualities inherent in them.

Apart from the organizations of forms and spaces mentioned above, there are additional principles that are used to create order in architectural compositions:

Axis : It is an imaginary line in space about which forms and spaces are arranged in a regular or irregular manner. Axis must terminate at both of its end by significant form or space.

Symmetry : Balanced arrangement of equivalent forms and space on opposite sides of a dividing line or about a center or axis. Either an entire building may be organized symmetrically or only a portion may be symmetrical and organize in irregular pattern of forms and spaces about itself.

Hierarchy: Hierarchy results when differences in degrees of importance are attached to forms and spaces according to their role in the overall composition. Hierarchy can be created by variation in sizes, shape or placement of elements according to their relative degree of importance.

Datum : A line, plane or volume to which other elements can relate because of its regularity, continuity and constant presence. A datum must have sufficient size and regularity to the noticed.

Rhythm : It is fundamental notion of repetition as a device to organize forms and spaces. It is a patterned reoccurrence of motifs at regular or irregular intervals.

Repetition : Arrangement of elements according to their common visual characteristics. The individual elements may have their non identity, they need not be identical.

Transformation : Manipulations done to the prototypical model as per the requirements of the specific conditions. It requires the understanding of the fundamental nature and structure of the model in order to create finite permutations and incorporate them in design.

Pre-historic examples are centralized organizations combined with linearity. Greek cities are the example of grid organizations and their buildings are linear in dimensions. Romans used axially organized centralized spaces. This can be witnessed in the design of their buildings as well as cities. Gothic churches and towns were based on centralized organizations. Renaissance laid emphasis on linear and centralized spaces. Islamic architecture is an example of radial layout while Hindu architecture is organized according to centrality and linearity. Modern architecture used all types of spatial organizations.

4.4. GEOMETRY AS CIRCULATION

Circulation in architecture is related to all the functions depending partly on the purpose and partly on the arrangement of masses and spaces in and around the building. The arrangement and configuration of use-spaces and the pattern of movement together generate the geometry of the building as they respectively determine the static and the dynamic components of which a building is constituted. The creation of one component automatically generate the system of the other and vice-versa depending upon the architect's decision as to generate which component first or articulate both of then simultaneously as per the design philosophy and context. Movement pattern enhances imageability; it helps in consolidating the very essence of the building in users' mind. The geometry of the circulation space determines the formal qualities of the built environment around it: Movement within a large space may also be defined by placing the activities and arrangement of furnishings. There are numerous varieties in which use-spaces and circulation can be combined to form the intricate non-repetitive patterns. It is the quality of good circulation space that successive additions can be made easily allowing the original building to be expanded as and when needed.

As a person moves in time through a sequence of spaces, circulation acts as a perceptual thread that links different, spaces inside or outside a building together. Apart from any functional value sometimes the movement path carries symbolic connotations as well. The movement along path is identified with the idea of change i.e. moving from profane to sacred, from darkness to enlightenment etc. In this situation the geometry of the path becomes even more important.

APPROACH

The first phase of circulation is approaching the building i.e. coming closer to a building from a distance in order to see, experience and use the spaces within and /or around it.

The approach may follow simple path or a circuitous route. Approach to a building is of mainly three types as discussed by Ching (1996) [8].

Frontal : The geometry of this approach is linear/axial straight path. The whole front façade or an elaborated entrance may be the visually terminating point.

Oblique : This type of approach enhances the effect of perspective on the form and front facade of the building. To emphasize the external visual experience of the building the path can be redirected many times to prolong this experience before entering.

Spiral : A spiral approach further emphasizes the three-dimensional form of the building as one move around the perimeter of the building. This type of approach helps in perceiving the overall external geometry of building. It also helps defining the basic geometry of the building. In the case of non-frontal approach only fragments of building can be experienced from various positions around the building. The next step after approaching the building from a distance is to enter inside it. The entrance can be defined as act of penetrating into building/ into a room within a building or into a defined field of exterior space. The geometrical configuration of the entrance may be in conformity with the form of the spaces being entered or in contrast with them in order to emphasize its own identity. It may vary from a single hole in the wall to an articulated ceremonial gateway. The location of the entrance in relation to the form of the space being entered will define the configuration of the path inside along the pattern of use-spaces. The entrance becomes prominent if it is placed in the geometric centre or perceptual centre of facade which may be off-centric. Projected porticos, porches marquees and their geometry state a definite welcome to the building. Steps and ramps add a vertical dimension to this experience.

CONFIGURATION OF THE PATH

All paths are essentially linear in nature, have a definite starting point from where one moves through varied space sequence to his destination which unfolds the geometry of the building. Pedestrians enjoy greater freedom of movement along a path, the configuration of the path further helps to reinforce this quality. The form and scale of entrances and paths convey symbolic as well as functional distinction between hierarchy of spaces. The geometry of the path may strengthen a spatial organization by running parallel to it or it may create a contrast by becoming visually distinct and making its own statement. There are varieties of configurations of the path; a building may have any one or a combination of these as discussed by Ching (1996).

Linear : A straight path may act as a dominant statement for the organization of series of spaces, in order to define geometry; in addition it can be curvilinear or segmented, intersect other paths, have branches or form a loop.

Radial : In radial configuration, linear path extend from or terminate at a central point i.e. radial configuration may be centrifugal or centripetal but in both the cases it emphasizes centrality.

Spiral : It is a single continuous configuration originates from a central point, revolves around it and becomes increasingly distant from it. It reinforces the continuity of space. It is extremely effective geometrical shape where movement is the most dominant feature of the building.

Grid : Two sets of parallel lines when intersect each other at regular intervals form a grid.

Network : These kinds of paths are the results of developments/additions which take place over a period of time. It consists of paths connecting specific points, thus a network may have irregular, asymmetrical geometry.

Composite : A building may have more then one types of configurations of paths as per the requirements. In order to bring legibility in circulation, a hierarchical order may be established in the circulation system by incorporating variety in form, scale, length and placement of path.

PATH-SPACE RELATIONSHIP

As mentioned articulation of path and space i.e. of dynamic and static components together formulate the geometry of the building; paths are related to spaces in three ways.

Path Pass By Spaces : Spaces in this case are arranged along the path. This relationship is flexible in nature. The integrity and identify of each space is maintained. If the spaces do not abut the path but are at a distance then the mediating spaces provide interesting link between the path and the space creating variety in circulation system.

Path Pass Through Spaces : In this system, the path is decisive factor in the overall geometry of the building. It may pass through the different spaces in a variety of ways i.e. axially, obliquely or along the edge of the space as per the requirement and design philosophy. At some places, it may merge with the spaces around it.

Path Terminate in A Space : This system establishes the symbolic or functional importance of spaces. The location of the space determines the configuration of the path. The form, scale and proportion of a circulation space must accommodate the movement of people as they promenade, pause, rest, or take a view along its path. An enclosed circulation space in the form of corridor relates to the private spaces along it through punctures or entrance doors in a wall. Path open on one side provide visual & spatial continuity with the linking spaces. Path open on both sides becomes visual extension of the spaces through which it passes.

The form of the circulation pattern carried prominent symbolic connotations among different cultures in history. The combination and merging of the linear and centric movement pattern found its architectural and symbolic expression in Pre-historic as well as greek and roman architecture. Renaissance being architecture of addition, the movement pattern had well-defined centric dominated geometry which gave way to fluidity during baroque times.

Centric and linear movement patterns are predominant in hindu sacred architecture owing to the symbolism attached to it. Islamic architecture is also characterized by well-defined geometry. Linear, grid and centric movement pattern found special significance. Well-defined movement patterns impregnated with varied meanings were the definite tools for the creation of order in architecture.

In 20th century, the approach towards movement became strong philosophical basis of modern architecture. Futurism, the basis of which was speed and all sort of dynamism, was born in Italy, for the objective of cultural rejuvenation of the country. The invention of Cubism, also based upon the movement in space and time, had a profound effect on modern architecture. The concept of flow of spaces, associated with visual movement had been a leading phenomenon determining the basic geometry of the works of modern masters.

4.5. GEOMETRY AS ARTICULATION

Architecture comes into existence through the volumetric combination of a large number of elements. Articulation is the way in which the elements and surfaces of a form integrate cohesively to define its shape and volumetric geometry. In this sense, articulation is unique as it helps defining character specific to a building. Articulation emphasizes strategic breaks enhancing the autonomy of individual parts and strengthens the role of the different constituent elements forming a complete whole. Articulation in architecture can be done of materials, of architectural elements, of function or of meaning making building expressive of its own nature.

The treatment of corners and openings are useful tools for surface articulation. Articulation can also be done in relation of building to the ground, detailing out the capping with a cornice and a roof, in cladding etc.

Corner can be emphasized in various ways; it gets special status as a feature of the building. Emphasis can be laid by the change of material, color, pattern, texture. The recessed corner also emphasizes the junction by separating the adjoining planes. On the other hand corner stones are markers of stability of the wall and provide a lateral frame to both the faces. Sharp edge determines the specific geometry of each face imparting visual clarity to form. Continuity can be accentuated by rounded or smooth corner.

Light is also a powerful medium of articulation. It articulates a surface providing variety of visual experiences in different hours of the day. Articulation of light has strong functional and symbolic connotations apart from modulating surfaces. "Our perception of shape, size, scale, proportion and visual weight of a surface is influenced by its properties and it visual context" (Ching, 1996) [8].

VISUAL WEIGHT

The expression of a surface in terms of lightness, massiveness, boldness, dominating, receding etc.

Color : A contrast in the color of a surface from the surroundings clarifies its shape. The visual weight of the surface can be modified by tonal value of color.

Texture : The tactile quality helps determining the visual weight of the surface

Optical Patterns : Generation of patterns of different scales on the surface is a strong tool for its articulation and visual weight.

Massing : The organization of diverse masses into a meaningful composition helps defining the visual weight of a form.

Scale : The perception of size of something in relation to something else. It is comparison of one thing to other. It can be in relation to a surface or three dimensional form.

Human Scale : It is based on the dimensions and proportions of the human body as accepted standard compared with an object or space.

Visual Scale: It refers to the size of one thing in relation to the size of other in its context. It does not refer to the actual dimensions of things.

Hierarchical Co-operation of Different Scales : According to Salingaros (2000) [80], human beings organize complex distribution of various parts of building into different hierarchies. An observer reduces any complex organization into different groups/levels/scales. Repetition of similar units of almost same size determines one scale. A building and its parts can be subdivided according to different scales. Varieties of independent scales arise from the materials, structure and function which help expressing architect's idea. These hierarchical scales influence the observer as they facilitate the process of human cognition. Greatest buildings successfully integrate and articulate their different subdivisions into hierarchy of interconnected scales.

Specific techniques determine the co-operation of different scales. Firstly, two or more scales having units of the same size, called coincident scales, link through contact, or contrasting colors or shape. The clustering of such coincident scales establishes contrast. Units having complimentary shapes and colors generate rhythms and variety of patterns. Secondly, different scales can be linked by similarity, the bigger/higher scale units can be the magnified versions of units of lower scales. Magnification here does not mean the pure duplicacy, only a portion can be duplicated as long as similarity is recognizable. Thirdly, through the relative abundance of units of each scale a mathematical link is generated between two different scales; these try to visually balance each other. Human mind has the built-in capability to recognize the co-operation of different hierarchical scales.

Salingaros (2000) [80], proposes that for good hierarchical co-operation of different scales, the ratio between the two consecutive scales should lie anywhere between 2 to 4, preferably closer to 2.7 (the base of natural logarithm). Subdivision of parts should be carried down to the smallest scales near the limit of perception.

Geometry was applied in articulation in earlier civilizations. In Egypt, wall surfaces had incised relief and hieroglyphs, projecting vertical and horizontal bands. Decoration was based on patterns in circle, spirals and plant forms. The articulation of Egyptian columns manifested their vegetable origin. Later facades had colossal statuary. The Ziggurats of Mesopotamia were articulated with vertical bands projecting out of walls surfaces.

Apart from reliefs having human figures depicting some story, greek articulation was based on Doric, Ionic and Corinthian orders and optical corrections applied to facades. Romans broke their flat surfaces by attached columns and niches filled with classical statuary. Classical orders were used only for surface decoration of walls.

Romanesque architecture laid lot of stress on articulation Innovations in the form of wall passages, sculptural decorations and carved molding confined to capitals, doors, windows and arcades were applied. Capitals derived from Corinthian order were common. Cushion capital consisting of purely geometrical forms of cube and sphere combined were prominent.

Gothic articulation is characterized by tracery patterns of stained glass, walls had flowing forms of decorative patterns, sculptures in the form of human figures over the openings.

In Renaissance architecture, classical orders used to articulate façade. Palazzos have projecting cornices imparting horizontality. Michelangelo's' plastic approach to wall surface paved the way for Baroque curved surfaces and freedom of detail.

Articulation in hindu temples is done with idols of deities, more related to human proportions. In Islamic architecture geometry is extensively used in wall mass and decoration. Patterns were created on the principles of symmetry, repetition and change of scale using triangle and square as the basic theme.

Mostly, corners are used for articulation in modern architecture. Louis Sullivan, Le-Corbusier, Frank Lloyd Wright articulated their facades based on proportions and geometrical shapes. So every period and civilization had their own methods of articulation based on their philosophy, craft, materials and available technology using geometry in variety of ways.

4.6. GEOMETRY AS STRUCTURE

Structure of any kind is basically to reinforce or realize the ideas of architecture. Structure is used to define space, create units, articulate circulation, develop compositions and modulations. It is inherent part of the elements which are responsible for quality and excitement in architecture. It reinforces the variety of organizations in space and form and their geometry besides addressing the other functional issues.

The form of living organisms is a result of the action of forces on them, it is determined by the mechanical considerations. The force acting on a body not only is seen as the motion in the body but also by the very existence of the body itself whose permanence is based on the equilibrium of forces. The bones of the human body tend to follow the lines of stress in the case of normal distribution of forces." With this field of force, the whole skeleton and every part thereof, down to minute intrinsic structure of the bones themselves, is related in form and in position to the lines of force, to the resistances it has to encounter." (Thompson, 1975) [63].

Similarly in architecture structural elements span spaces and transmit their loads down to the foundation through vertical supporting members, these may be columnar, planer or combination of various types. The size and scale of these structural elements depend upon the load transmission and hence can be considered as the visual indicators of the size and scale of the spaces they enclose. In the case of membrane structures or space-frames stability depends more on their geometry while their elements are very thin.

Structure is used to bring order in architecture. Greek architecture is the exclusive example of this type. The lower diameter of the column was taken as the basic module for fixing all the other dimensions of the building thereby relating all parts with each other harmoniously. The dimension of the lower diameter of the column was not based on any predetermined fixed measurement. The proportions of the various parts of the temple were fixed according to the personality of the deity to which the temple was dedicated, based on the lower diameter of the column as the basic module but the underlying guiding principle was the proportions of the human body. For example, temples built in Doric order used to share the proportions of masculine body for strength and beauty while those of Ionic order shared the feminist slenderness and beauty in their proportions of various parts at different scales. Apart from the structural role of the columns, they were also used to define different spaces, interlocking them with adjacent ones. Romans used pure forms in their architecture to determine a specific geometric order. The definite geometric organization is seen in the structural elements in the great halls of the baths, basilicas apart from major buildings like Pantheon, Colosseum etc and in the organization of their cities.

Romanesque architecture is characterized by skeletal structure and semi-circular arch. The originality of gothic architecture is submitted to the ultimate development of compressive structural system, based on vaulting and buttressing, integrated with architectural intentions of highest order. Gothic was age of experimentation in structure.

Thick load bearing walls and pyramidical or conical shikhara based on corbelling predominantly characterize the structural aspects of hindu architecture. The size and arrangement of structural elements were fixed according to the overall geometrical scheme.

The specificity of structure of islamic architecture is the placement of dome over cubical compartment. The transitional elements between square plan of cube and the circular base of dome are eight (octagon) and sixteen sided polygons. The architectural spaces are defined by colonnaded and arcaded structure. Structural proportions determined the geometry of religious buildings.

Japanese architecture is also purely ordered by structural proportions. The traditional unit of measure, Ken, originally varied in size, used to determine the spacing between columns but was soon standardized as an aesthetic module-guiding structure, materials and space proportions. Ken modular grid was used in two ways in designing. In both the methods it determined as center to center spacing of columns further determining the three dimensional proportions of individual rooms as well as the overall building.

The works of P.L. Nervi and Buckminster Fuller are outstanding in relation to the integration of structure and architecture in modern times. Structure exquisitely becomes source of form as an image, in their work. The same qualities can be seen in the works contemporary architectures like Norman Foster, Richard Rogers and Renzo Piano. The geodesic dome of Fuller has regular and simple geometry while the architecture of Nervi is the result of structural modulations and material qualities. Their structures are not merely showing forces in equilibrium but determine the architectural expression of the era. Though the underlying purpose of structure is to support but the different masters of 20th century through varied expressions to structure impregnated it with different meanings in their buildings. In any great piece of architecture, the structural design, the form, the material texture and qualities jointly determine the geometry of the building, the light and the place. Due to the action of external forces, different types of stresses develop in a structure. There are three types of stress – compression, tension and flexure.

Compression : When two equal the parallel forces press the volume of materials from opposite sides along a common axis, the distribution of stresses in the material will tend to press the particles towards each other. This type of stress is compression.

Tension : When two equal and parallel forces stretch the volume of material from opposite sides along a common axis, the distribution of stresses in the material will tend the particles to be pulled apart. Such a stress is called Tension.

Flexure : The forces in this case are parallel to each other but act along different vertical axis separated from each other. The total magnitude of the two upward forces on either side of the volume of material is the same as the total magnitude of the forces acting downwards. The resultant of such an alignment of forces cause the volume to bend, the stress in this case is called flexure.

The overall movement pattern of forces in a structure due to different types of loads acting simultaneously is called load-transmission. The ultimate aim is the balancing of forces safely transferring the load to the ground.

According to Pramar (1973) [54], structures are divided into four main categories according to load transmission. These are right-angled, spherical, diagonal, and spatial

RIGHT ANGLED STRUCTURES

These consist of the junction of vertical and horizontal elements. Vertical elements are columnar or point supports and walls or continuous/planer supports while the other ones are slabs or horizontal continuous supports and beams or horizontal linear supports.

Right Angled Load Transmission : The simplest method in which horizontal elements are simply placed over vertical ones without going into much technical details, based on experience. The joints may or may not be filled.

Non-Rigid Right Angled System : Here again the horizontal elements are simply placed over vertical ones, the junction between them is filled with mortar in the case of stone or brick walls and nails, bolts in the case of wood. The elements behave independent of each other under the action of load. The non-rigid junction here does not transmit the effect of flexure in the horizontal member, due to loading, to the vertical members. Vertical members remain under simple compression. The deformation occurs in horizontal members without affecting the vertical ones. Various combinations of non-rigid system include-vertical point support + horizontal linear support, vertical point support + horizontal continuous support, vertical continuous support + horizontal continuous support.

Rigid Right Angled System : In this system stresses due to flexure induced in horizontal members are transmitted to the vertical ones also. The transmission of flexure continuous till the joint is intact. The junction that transmits the flexure is called rigid junction, most of them are monolithic in nature generally found in RCC and welded steel. In wood, junctions can be made rigid with the help of straps. Considering any two connected monolithic elements who act in one plane as one element in monolithic structures, we can sub divide them in three categories. Vertical linear element, vertical continuous element, horizontal continuous element.

Structural systems are combinations of these three elements viz vertical linear element + horizontal continuous element, vertical continuous element + horizontal continuous element. The multi-storied 'tree' like structure where strength depends upon solid core of walls centrally placed or located symmetrically in case of more than one cores, going through out the buildings and rigidly anchored with the foundations is the example of vertical linear support and horizontal continuous support.

SPHERICAL STRUCTURAL SYSTEM

Structural system in which loads are transmitted along curved continuous path is called spherical system. Apart from pure spherical forms, elliptical, parabolic and horizontal-cylindrical forms are also part of this category. Load on the curved bodies are simultaneously distributed in numerous directions. All kinds of domes are well known examples of this system along with arch system, vaulting and shells.

Arch System : Purely compression member, load transfers along the curved surface to the feet. Maximum chance of displacement of material is along the horizontal axes at the widest points where thrust is maximum. Arch is structurally two dimensional element acting in only vertical plane so does not enclose space, only defines space and forms openings.

Vaulting : Parallel translation of arches creates vault. It is also stressed the same way as arch, therefore in compression. Being three dimensional, enclose space over rectilinear plan. In medieval times, first of all six main stone ribs were constructed along sides and diagonals and then the gaps were filled by smaller cross-arches between nearest ribs in brick.

Dome : Compression member results from the rotation of arch along vertical axis. It is stressed in the same way as the arch. Continuous thrust along circular edge at the base. Monolithic RCC dome does not behave like simple arch at the point of load, the whole material comes into play and the resistance capacity is increased.

Shell System : It has greater resistance to evenly distributed loads, generally made in RCC; strength is due to curvature and thinness. It is suitable only for single stress structures of either pure compression or pure tension. It can be used only as space enclosure because of little resistance to heavy point loads.

DIAGONAL STRUCTURAL SYSTEM

The load is transferred diagonally to the vertical supports; instead of undergoing flexural action of beams, the stresses in the system are either compression or tension or a combination of both.

The Truss System : The stresses in truss are compression and tension. The truss acts in one plane and so must be repeated at certain intervals over vertical supports to enclose a space. It is made of wood or steel and suitable over rectilinear space.

Flat/Folded Plate System : It is made up of RCC and thickness is like those of shells. This system works only in compression.

SPATIAL STRUCTURAL SYSTEM

In space-frames loads are transmitted along two or more flat planes. It may be a combination of trusses running in two directions at right angles to each other. If the trusses are rigidly connected they will act as monolithic structure. Since the load is transmitted along more than one plane it encloses space. There can be varied combinations of space structures. Geodesic done is an example of this type.

GEOMETRY AS SEISMIC SAFETY OF STRUCTURE

During earthquake the ground below the building moves exerting fluctuating dynamic loads, the building suffers primarily because of horizontal forces exerted on a structure which is generally designed to carry gravity loads. Apart from structural design, geometry of the building plays an important role from the seismic design point of view.

Regularity and Symmetry : Symmetry and regularity in plan and elevation is desirable. Symmetry in plan configuration and structural symmetry both are important; structural symmetry is when centre of mass and center of resistance are located at same point. Lack of symmetry in plan about both the axes leads to torsional effects and can be destructive. Ideal plan shape should be as simple as possible. Circle and square are the best shapes. A box-shaped building rectangular in both plan and elevation is stronger than L-shaped, U-shaped or zigzag-shaped building with attached wings. Symmetry is also desirable in the placement of openings.

Proportions : The overall proportions of the building are more important than the absolute size. To secure the building against turning; height to depth (width) ratio should be restricted to 3 or 4 i.e.

$$H \not> 3\text{-}4\ W \text{ and}$$

Length to width ratio should be limited to 1 to 2 i.e.

$$L \not> 1 - 2\ W$$

Building Should Be Light Weight : As the weight of the building components increase, the dynamic forces produced during earthquake increase. Building materials with high strength to weight ratio is desirable. Timber is suitable for low-rise, structural steel for high rise, R.C.C. and reinforced masonry for medium rise buildings, stone and brick are least desirable.

Structure Should Have Uniform and Continuous Distribution of Strength, Stiffness and Ductility : During earthquake structural weakness create problems. These weaknesses are due to sharp changes in strength, stiffness and ductility.

Non-structural Components Should Either Be Properly Integrated or Effectively Isolated From The Basic Structural System : Unless properly designed, the parts that are supported by or attached to structure will deform during movement in earthquake thus creating destruction.

STRUCTURAL MATERIALS

Used to construct a structure and withstand the substantial loads for which it is intended without going into significant deformation, according to Pramar (1973) [54].

Wood : Cellular in nature, very durable, resistant to both compression and tension in the direction of fibers, less resistant at right angles. Life span is less in comparison to brick or stone.

Brick : Homogenous porous material, used in compressive structures as it is strong in compression and weak in tension.

Stone : Homogenous, hard, very durable, very strong in compression, tensile resistance is less but not insignificant.

Concrete : Hard, durable, homogenous. It is of two types- in-situ and pre-cast. It is very strong in compression with less tensile strength.

Reinforced Cement Concrete : Strong in compression and tension, degree of resistance can be manipulated as per stress situation, great versatility to forms.

Iron : It was precursor to steel, very strong in compression and weak in tension, was used as a substitute to stone.

Steel : Homogenous, impervious to water, hard, great tensile and compressive resistance.

Material/space Ratio : The volume of material used as a percentage to the spatial volume created:

$$\frac{\text{Volume of material} \times 100}{\text{Volume of space created}} = X\%$$

The smaller the percentage, the more efficient is the material.

STANDARDIZATION

It is the process of formulating and applying orderly approach for best operation in present situation at the same time determining future development. It is done for proportioning different parts of a building and ensuring the co-ordination of dimensions between different parts and the building itself. It has three types:

Absolute Measures : These are based on the principle of modular co-ordination. Size of one unit is fixed as standard module and the other units are multiples of it. The size of module may vary as per requirements

Relative Measures : The specific relationship of one dimension to the other in the same component or among different components for symbolic and visual references. Greek orders are the best example of relative measures.

Preferred Measures : These consist of chain of interrelated dimensions specifically created and utilized for aesthetic and functional reasons. Corbusier's 'Modular' is the most suitable example of this system.

NATURAL LIGHT

Natural light may be an integral component in the design idea or be the consequence of design decisions made about the form and space of a building. Natural light whether it enters thro' a wall plane or thro' sky light in the roof plane, directly or indirectly, articulates the form and animates the spaces and surfaces through various hours of the day through out the year thereby adding to the dynamic quality of architecture. It reinforces the geometry, structure and enhances the symbolic and visual contents of the building. There are qualitative as well as quantitative differences in terms of impact of light depending on the way it enters the enclosure. The location and orientation of the opening becomes more important as compared to size in terms of quality of daylight the room receives. Natural light entering can be direct, diffused or indirect either thro' walls and/or through roof.

Direct : Filters directly, provides high degree of illumination creates sharp patterns of light and shade and crisply articulates the form within the space.

Diffused : When the opening is oriented away from direct sunlight, the enclosure receives ambient light from the sky vault overhead. Light entering is fairly constant in nature. Screens/louvers/projections are attached sometimes with the opening to reduce the intensity of light and affect its distribution in the enclosure as well.

Indirect : Reflected light enters the enclosure; light from openings first hit a surface and then it gets reflected to the concerned space. Illumination level may be high or low as per requirement.

CHAPTER 5

THE CASE-STUDIES

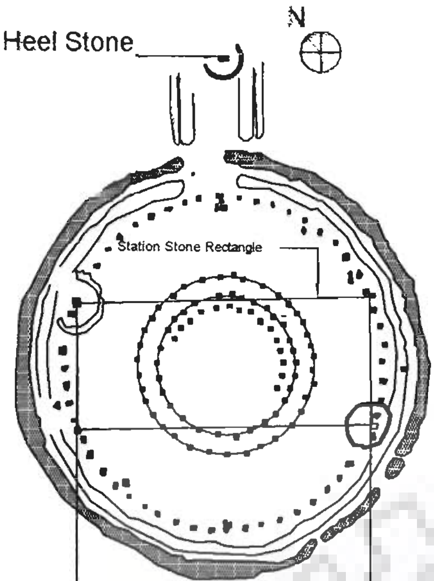
5.0. INTRODUCTION

The buildings for analysis have been selected according to the research methodology and analytical procedure set for the achievement of desired objectives. Each selected building is discussed very briefly describing the geometrical systems incorporated in each of them and analyzed in terms of its various elements as discussed in chapter 4 which cohesively combine to accomplish its final form.

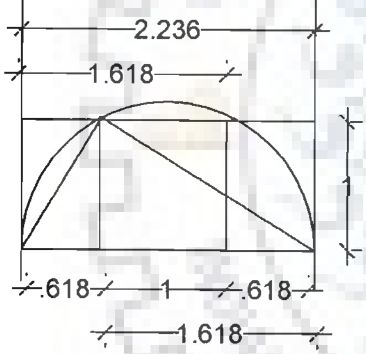
CASE STUDIES

5.1. STONEHENGE : SALISBURY (2500 – 1700 BC)

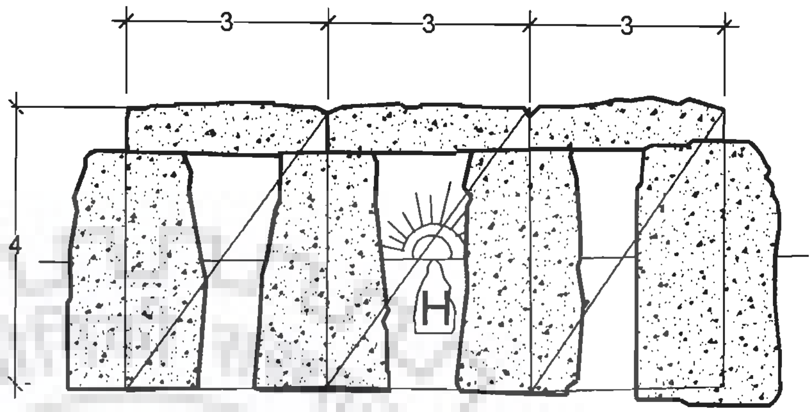
It was built in several phases on the sacred site of Salisbury. It is considered to be historically, astronomically, ritualistically and geometrically important structure. It consists of a series of concentric rings of standing stones with an alter stone in the center. The accuracy in erecting and positioning of stones in relation to astronomical phenomena is remarkable. The inner ring has a horse – shoe plan encircled by a ring of smaller uprights of sacred 'blue' stones and then an enclosing circle of sandstone monoliths. Each of the two vertical stones of the rings supports a single colossal lintel. The golden proportions, geometrical shapes in the form of circles and mathematical proportions in the form of 3-4-5 Pythagorean triangle are found to have been incorporated in this structure as seen in the figure. Plan of stonehenge is centralized around a vertical axis, it possesses a regular form with path passing through the spaces terminating in a main space. The overall



Plan



Plan Geometry



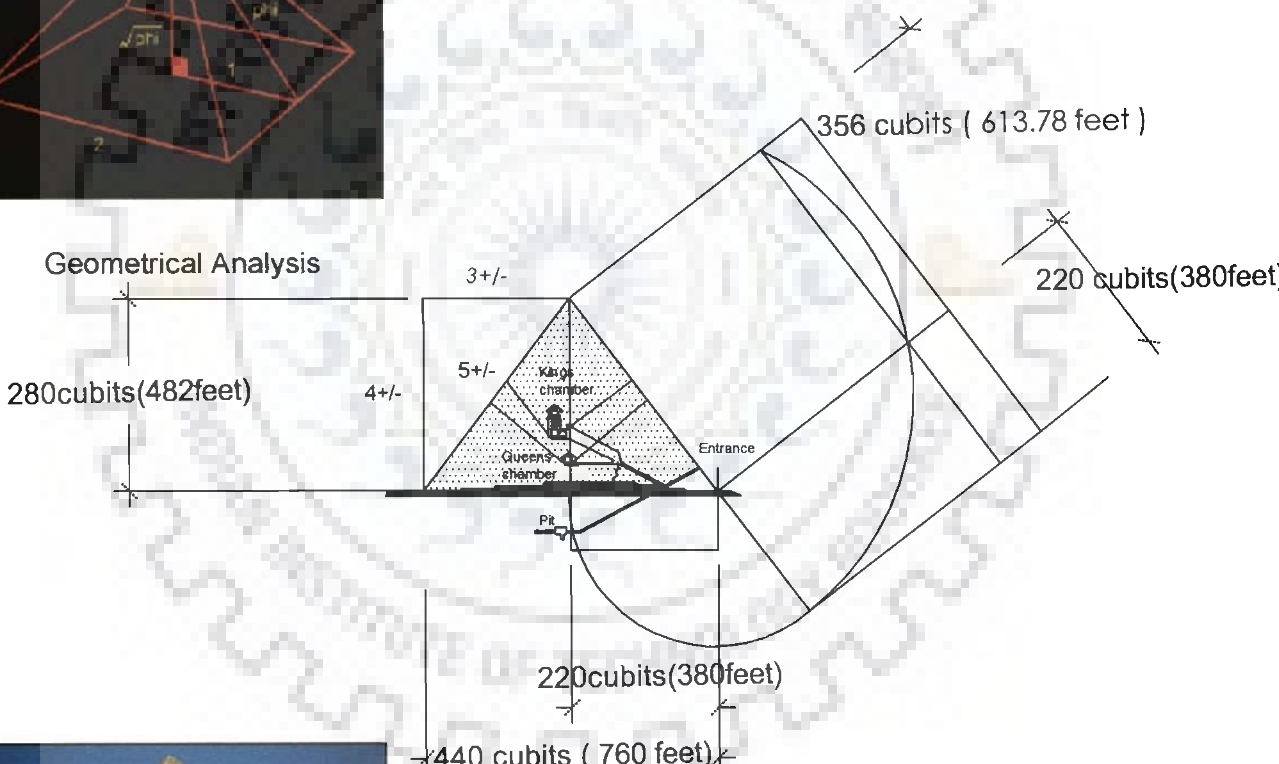
Pythagorean Geometry in Post & Lintel Structure

Fig 5.1 GEOMETRICAL ANALYSIS - STONEHENGE AT SALISBURY
Doczi (1994)

Pyramid of Cheops

The Three Main Pyramids Line-up
With The Belt Of Orion

Geometrical Analysis



Golden Section Relationship Doczi (1994)

Pyramid Of Cheops

Fig 5.2 GEOMETRICAL ANALYSIS - PYRAMID OF CHEOPS

composition has strong visual weight owing to the colossal rough textured stones.

5.2. PYRAMID OF CHEOPS : GIZEH (2650 – 2540 BC)

It was erected out of cut stone. Many stories have been associated with this pyramid. It is considered to have astronomical and mythological significance. Many authors have related its physical qualities and details inherent in its form with those of the physical traits of earth. Khufu or Cheops' great pyramid is square in plan. The base of the pyramid covers about 13 acres. The angle of inclination of the triangular face is about 51.5^0. Accurate use of geometry in the form of golden proportions and use of pure geometrical shape is its distinguishing quality. It is regular in form with main linear gallery going inside terminating in the centre of structure. The approach ways to the all the three chambers inside the pyramid are oblique in shape. It is made up of system of right angled load transmission. Its regular form makes it safe from earthquake forces.

5.3. ZIGGURAT OF UR (2200 BC)

Erected by Ur-Nammu for the moon God Nanna, it stands within a rectangular court. It was a part of temple complex which served for the administrative center for the city. The mathematical proportions along with golden ones found to have been incorporated in this Ziggurat for spiritual and aesthetical qualities. It consists of three-stages surmounted by a temple at the top. Baked bricks face the outer surface which is inclined to the pronounced batter with regularly spaced flat buttresses. The outer faces encase the solid core of mud bricks. Ziggurat is accessed through three converging ramps from where a central stairway continued to the upper stages. The corners of

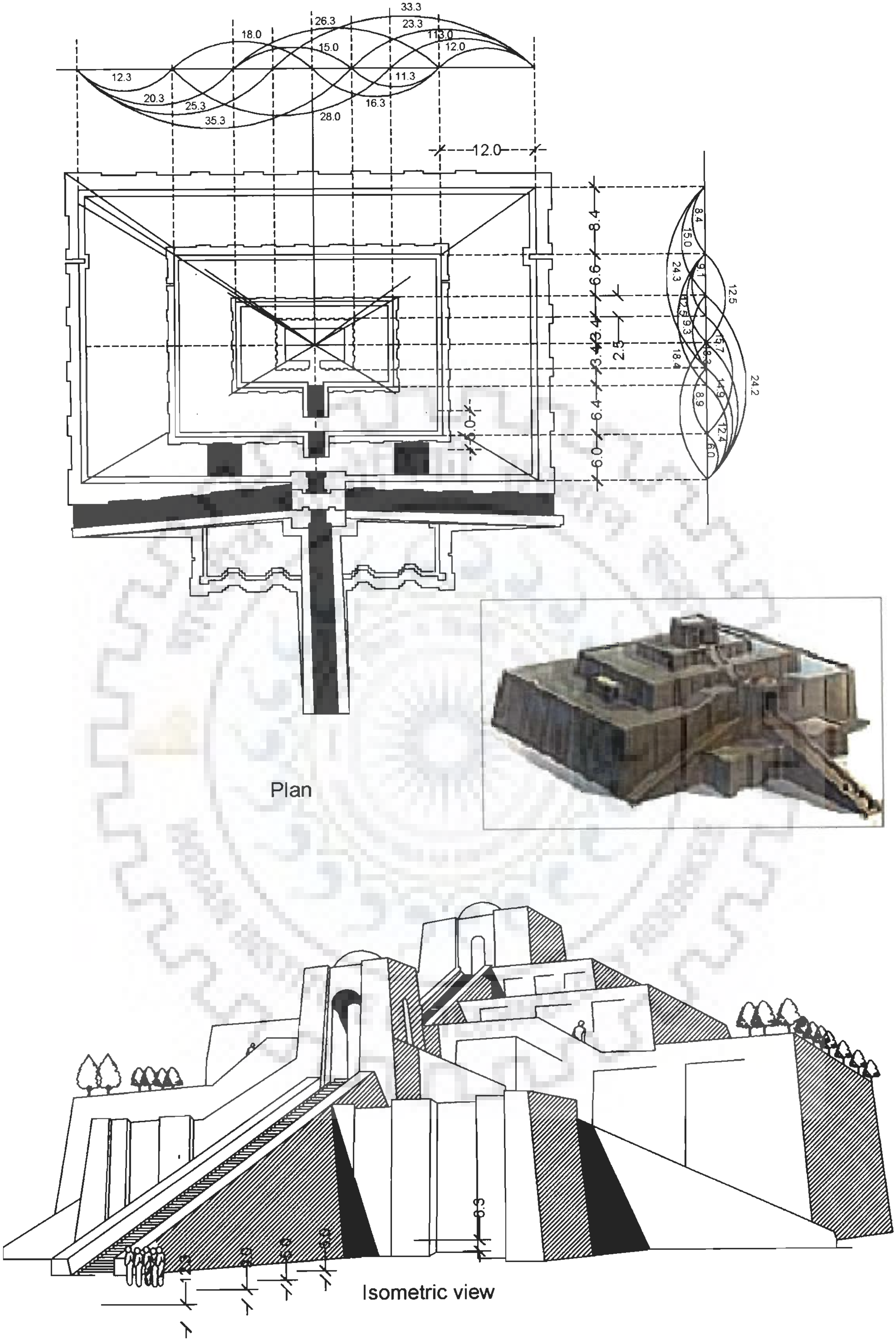


Fig 5.3 GEOMETRICAL ANALYSIS - ZIGGURAT AT UR
Doczi (1994)

Ziggurat are oriented to the compass points. It has regular, additive and centralized form with similar spatial organization. Smaller spaces are created from and supported by bigger ones at lower levels. It is strongly axial, symmetrical, and hierarchical with repetitive forms placed rhythmically. The approach to Ziggurat from main entrance is oblique. The movement paths pass through different levels terminating in a temple at the top. The visual weight is very strong owing to massive appearance, texture, color and optical patterns on the surfaces. It is built on right angled load transmission system with regular form imparting safety from earthquake.

5.4. PARTHENON : ATHENS (447-436 BC)

Designed by Ictinus and Callicrates, it is a rectangular temple consisting of Doric colonnade 8 on shorter and 17 on longer side. Phidias was the main sculptor. The temple stands on three steps with small intermediate steps on shorter sides. The cella consists of two rooms end to end having hexastyle prostyle porticos. In the main cella towards the end is the gold and ivory statue of Athena. This cella has internal Doric colonnade in two tiers necessary to support the roof timbers. This temple is the best example of optical refinements practiced by Greeks. The sculptural decorations are related to the Goddess Athena to whom the temple is dedicated. The pedimented temple front is approached obliquely. The orders were determined on the basis of human proportions with the lower diameter of the column as the basic module from which the dimensions of other parts of the façade were generated. Prof J. Hambidge (1924) [33] has done extensive research on the proportions of this building concluding that every part and its

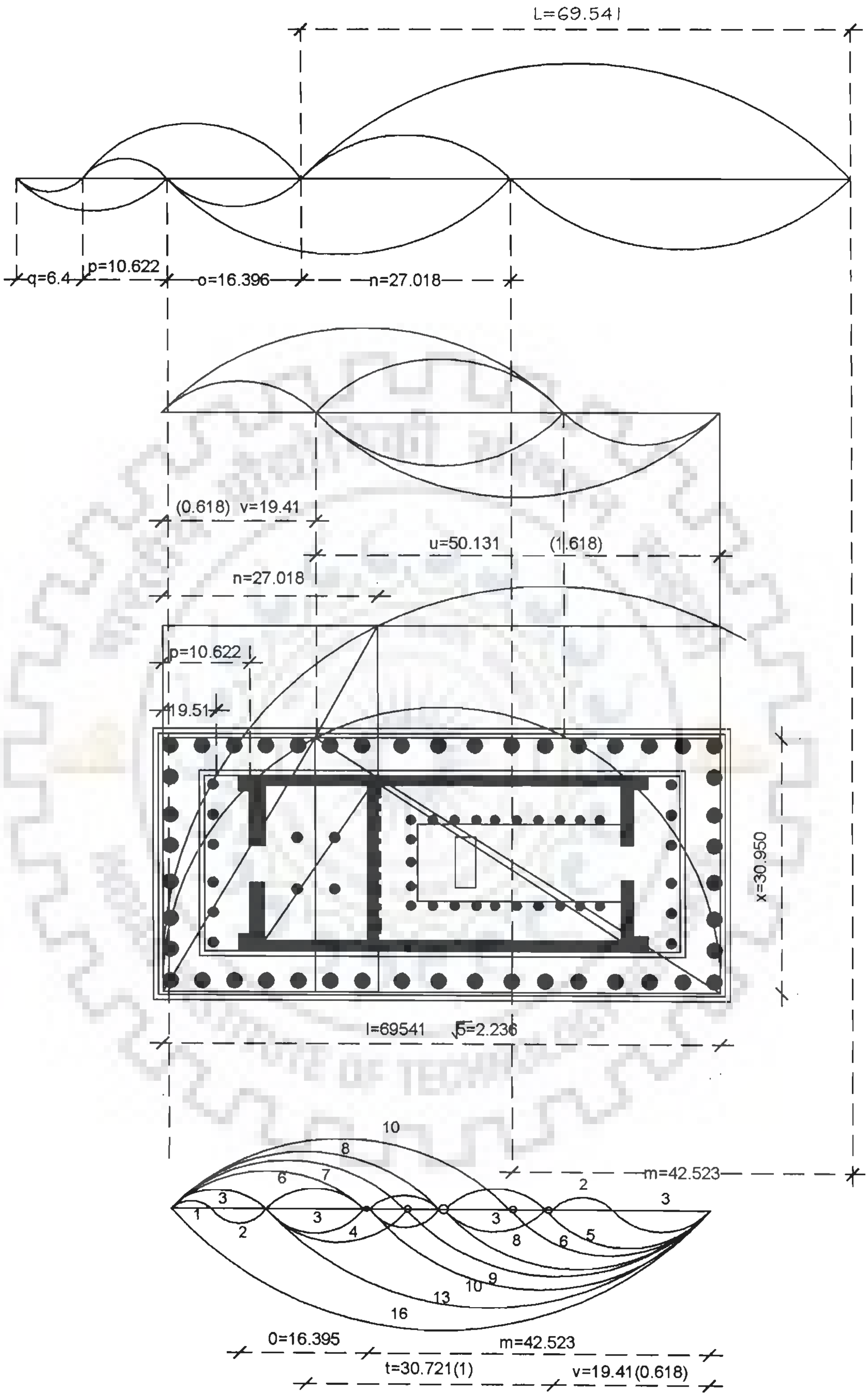
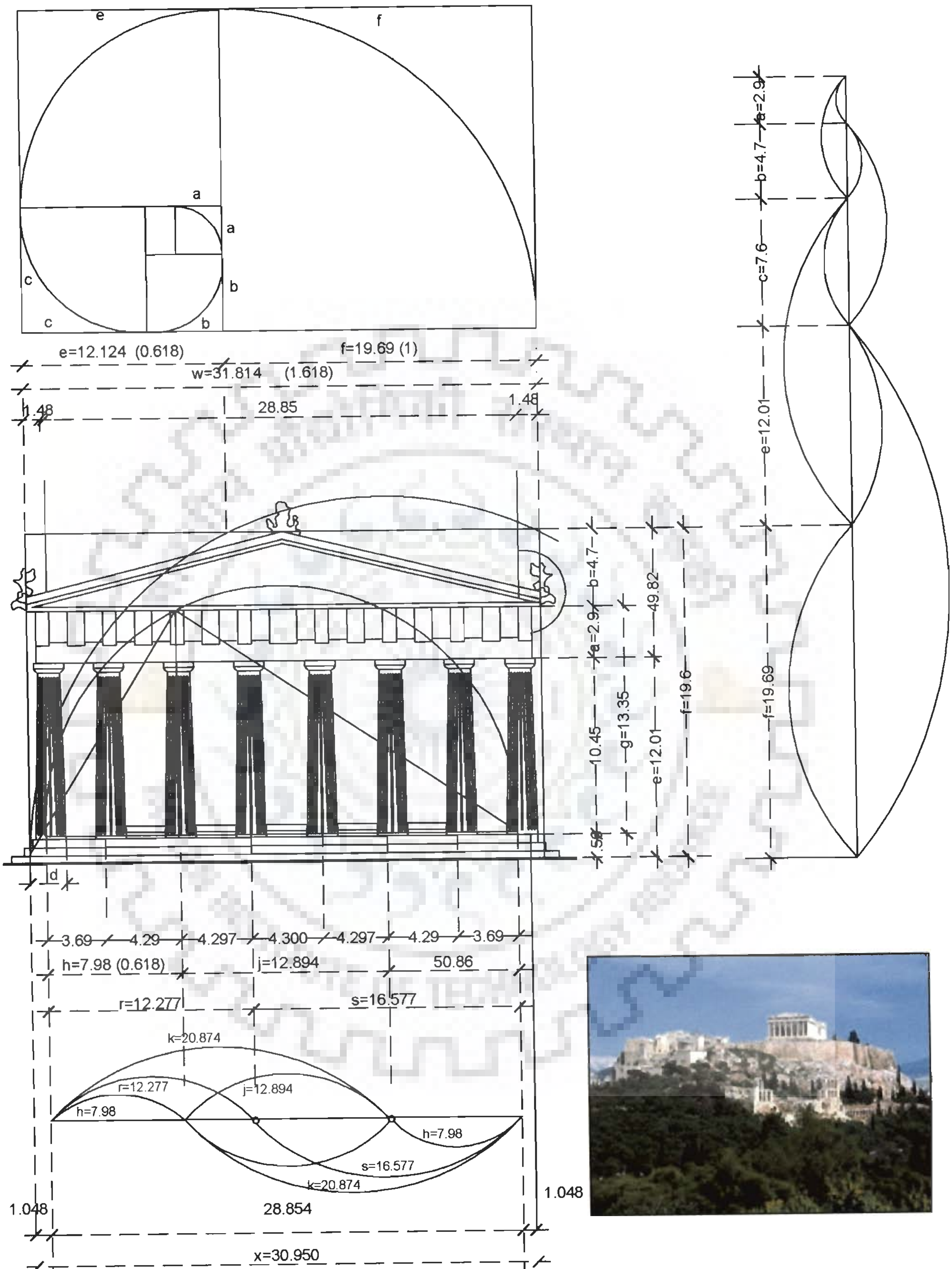


Fig 5.4 (a) GEOMETRICAL ANALYSIS - PARTHENON
DOCZI (1994)

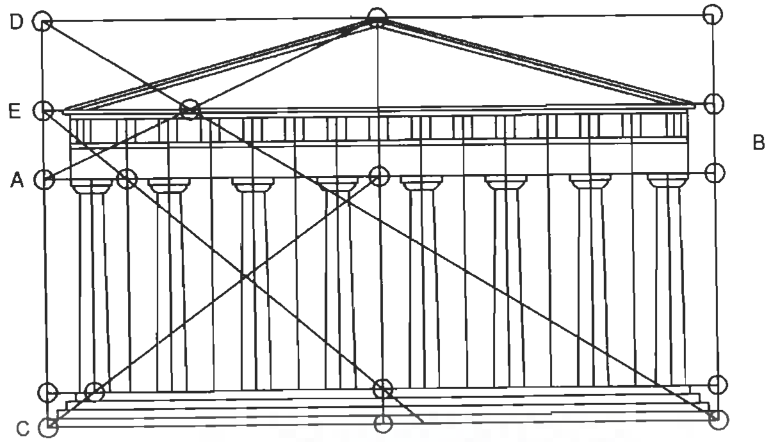
Some basic dimensions of front elevation in golden proportions

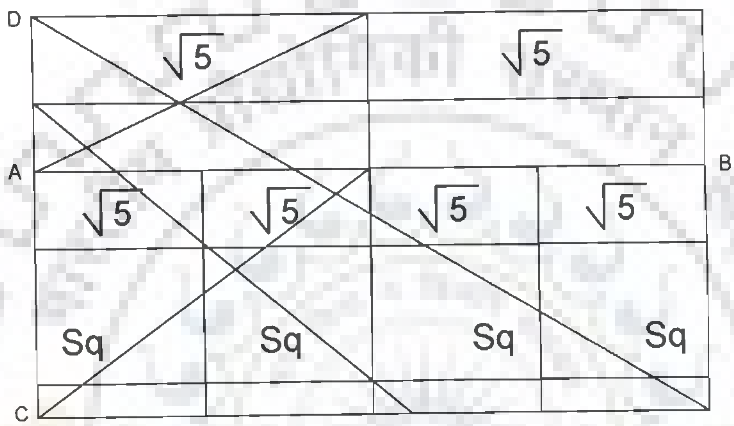


ELEVATION

Fig 5.4 (b) GEOMETRICAL ANALYSIS - PARTHENON

DOCZI (1994)





Dynamic Symmetry of Parthenon HAMBIDGE

Logarithmic Spiral Through Golden Propotion

ELEVATIONAL GEOMETRY - PARTHENON

Fig 5.4 (c) GEOMETRICAL ANALYSIS - PARTHENON
DOCZI (1994)

details are based on golden proportions. Various researchers have given different conclusions but the use of golden proportions is assured by most of them along with occasional use of geometrical ones to determine spiritual and visual qualities.

The form is regular and linear with different spaces placed adjacent to each other. The building is approached obliquely from the acropolis but has linear configuration of movement as one enters. The movement has a terminating point near the statue of Goddess. The visual weight is due to the monumental scale and high quality sculptural decoration. The structure is compressive with right angled load transfer system. The building is safe from earthquake predominately because of regularity and symmetry. Wood and marble are the structural materials used. Natural light enters through doors in the walls.

5.5. THE COLOSSEUM : ROME (70 – 82 AD)

Commenced by Vespasian, inaugurated by Titus in 80 AD and completed by Domitian, the Colosseum was the first permanent amphitheatre built in Rome. It is a vast ellipse with tiered seating of 50,000 capacity around a central elliptical arena. There are complex set of rooms below the wooden arena floor for wild beats and other provisions for staging. It has eight entrances. Eighty walls radiate from the central arena supporting vaults for passageways, tiers of seating and staircases. Circumferential arcades link each level at the outer edge. The three tiers of arcades on the façade are faced by three quarter columns and entablatures with Doric, Ionic and Corinthian in the first, second and third storey respectively. Above there is an attic storey with Corinthian plasters and small square windows placed in

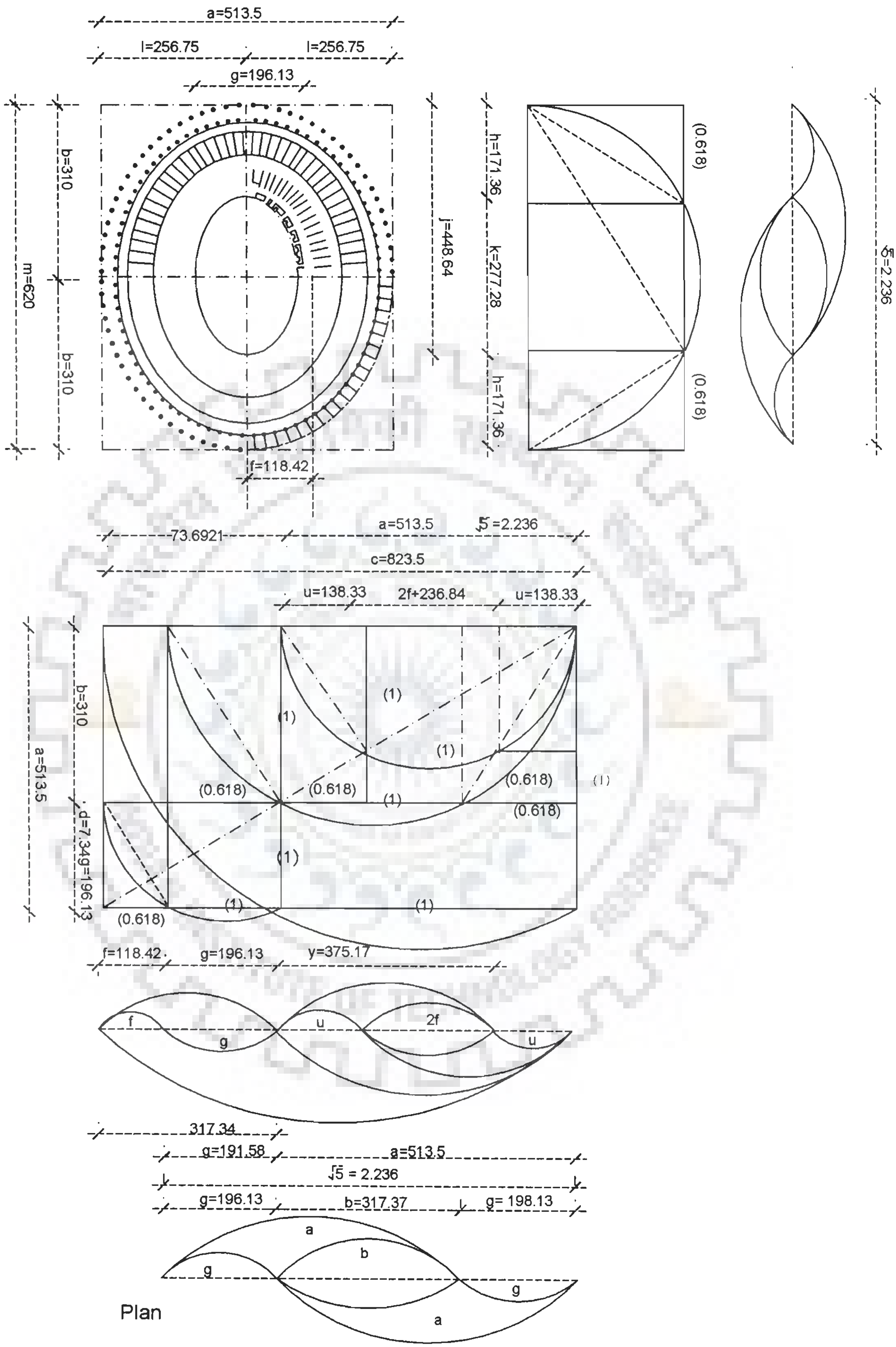
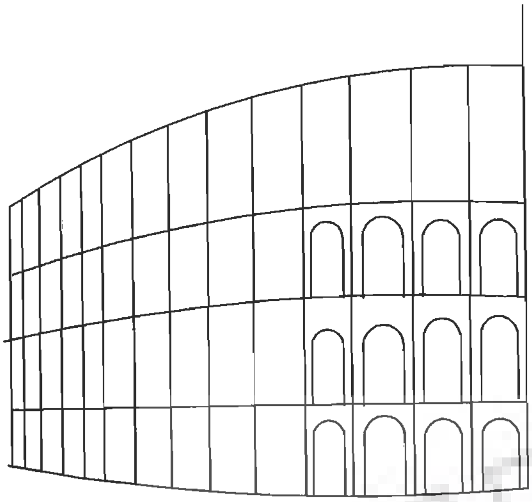


Fig 5.5 (a) GEOMETRICAL ANALYSIS - COLOSSEUM
Doczi (1994)



ELEVATION

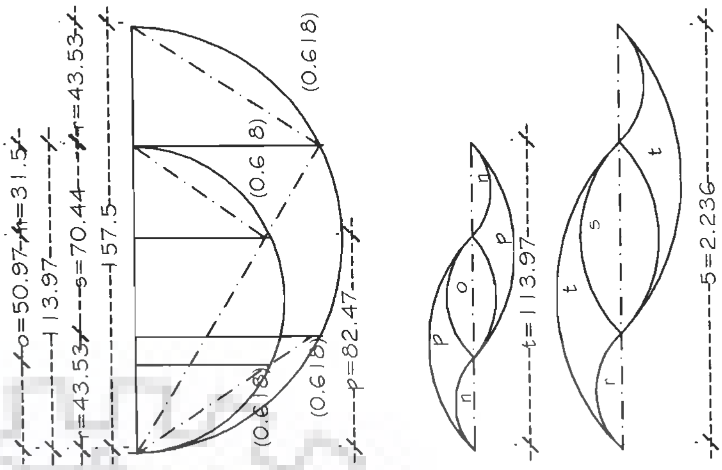


Fig 5.5 (b) GEOMETRICAL ANALYSIS - COLOSSEUM
DOCZI (1994)

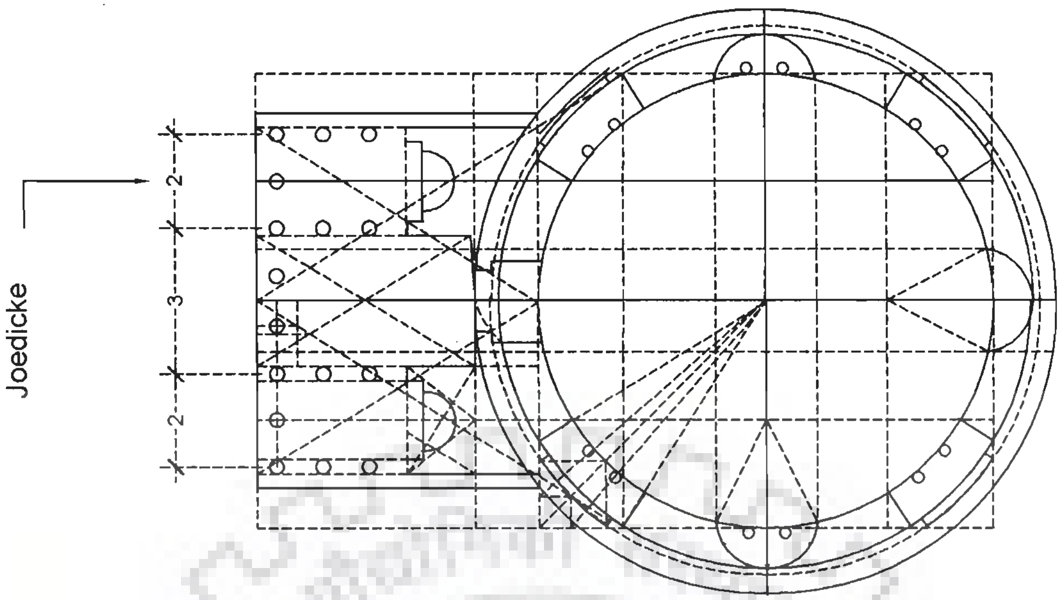
alternate bays. A canopy for shade was suspended at the top brackets and sockets.

The geometrical systems found here are golden and geometrical proportions as seen in the figure for monumental, aesthetical and functional reasons. The form is regular and centralized with main spaces placed within larger ones. The spaces are linked by common space. All the ordering principles are present in the composition. Configuration of path is mainly radial but has composite character also. Paths pass by spaces, through spaces and terminate in the main space. Visual weight is experienced through massing, surface texture, color and optical patterns. There is a good hierarchical cooperation among different scales of the composition. Arch and vaulting system predominate in load transferring, though right angled system is also used at some places. Owing to regularly and symmetry, it is safe from earthquake.

Concrete is used for foundation; travertine for piers and arcades. Walls of the lower two levels between piers have tufa infill, while brick faced concrete is used for upper levels and vaults.

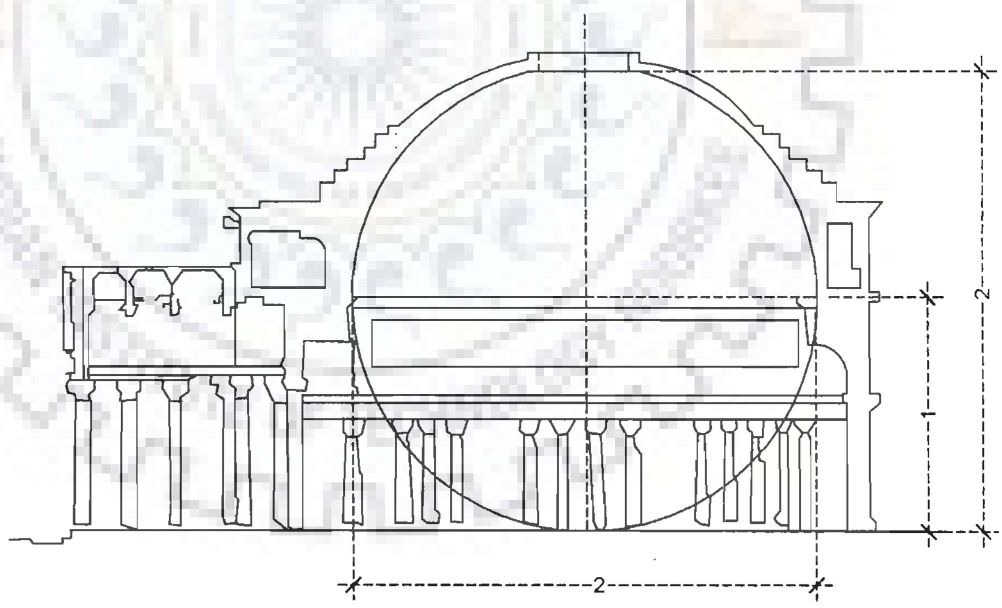
5.6. PANTHEON : ROME (118 – 128 AD)

It was first built by Agrippa, burnt in 80 AD and rebuilt by Hadrian as Roman temple but later converted into Catholic Church. It is one of the most prominent spiritual buildings of the world. The interior volume comprises of a sphere defined by the hemispherical dome above. The natural light enters through unglazed opening at the center of the dome. Recessed semi-circular apse opposite the main bronze door with three additional recesses, alternately rectangular and semi-circular, each flanked by paired monolithic columns,



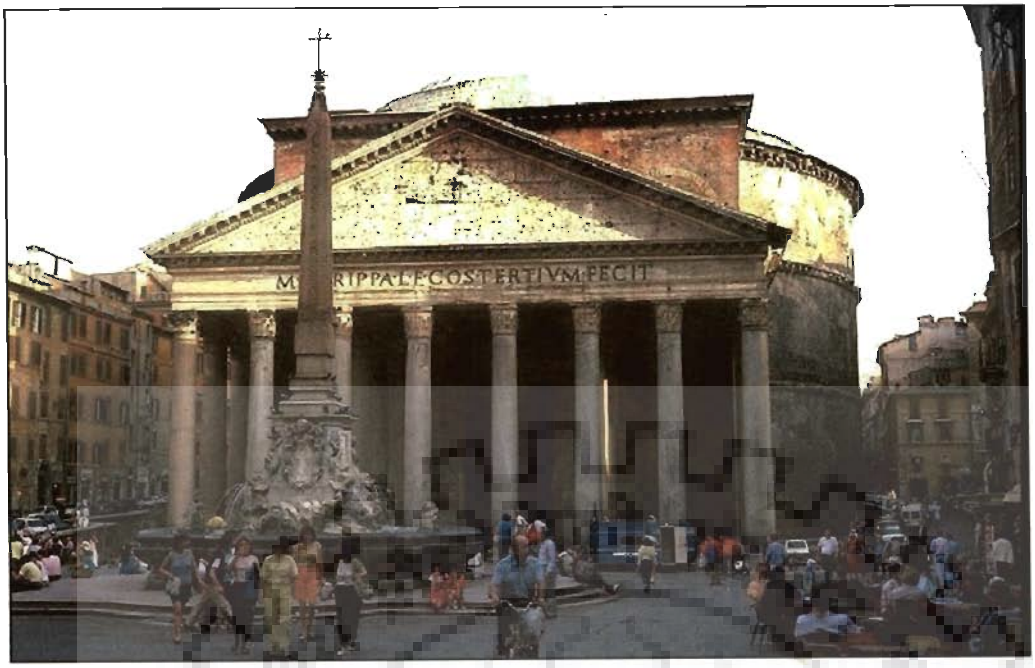
Plan

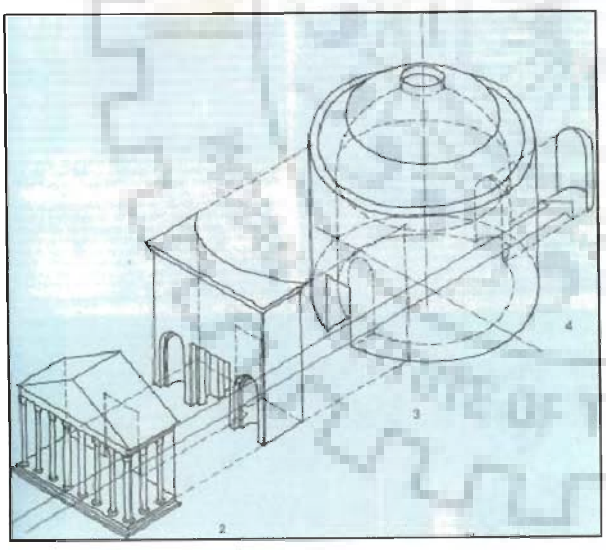
Pantheon Hormonic Analysis by Wiener (Ghyka 1977)



Geometry in Section Joedicke (1985)

Fig 5.6 (a) GEOMETRICAL ANALYSIS - PANTHEON





Isometric of Pantheon   Joedicke (1985)

Fig 5.6 (b) GEOMETRICAL ANALYSIS - PANTHEON

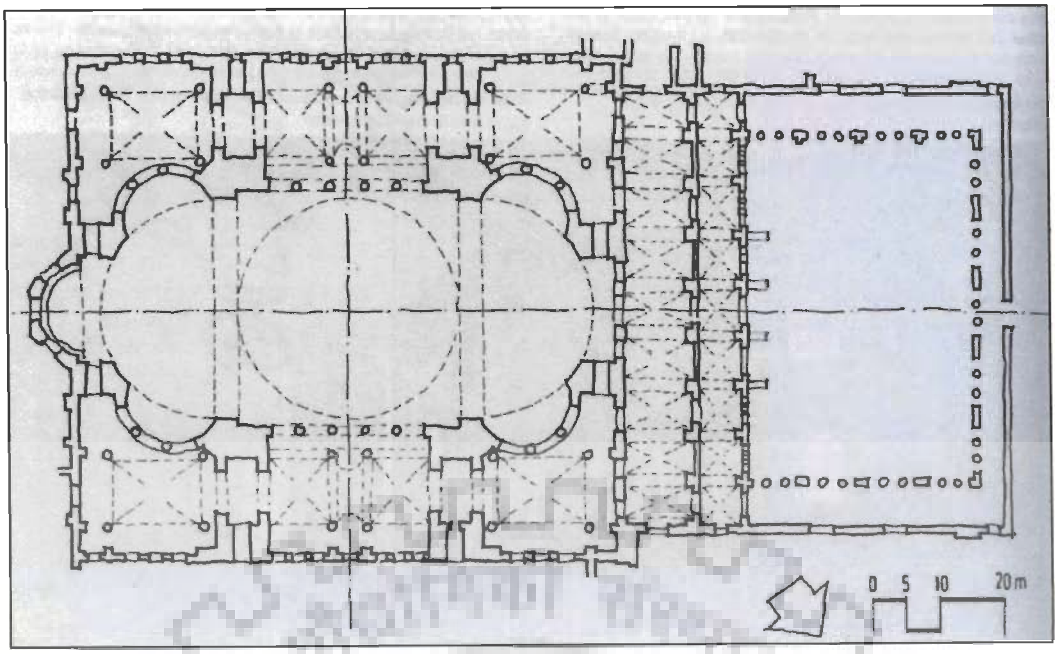
comprise the main elements of interior. Five rows of twenty eight coffers radiate from the central opening in the dome. It is constructed of stepped rings of solid concrete with diminishing thickness. Interior recesses and hidden voids hollow out the construction; it works more like the three tiers of relieving arches visible from the outside. The portico consists of three rows of eight columns with Corinthian capitals which are made up of Egyptian granite.

The structure is concretized through the use of musical proportions in different parts with strong volumetric geometry in the form of sphere. The composition is controlled by the use of regulating lines while module based proportions are incorporated in the columns. Apart from spirituality, desirable visual quality was also attained through these geometrical systems.

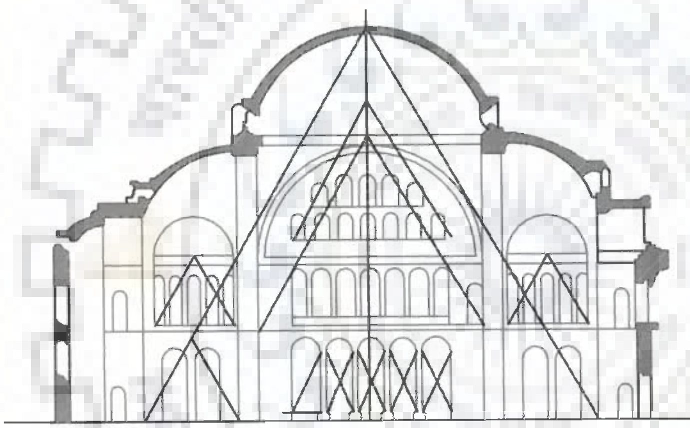
The building is centralized and additive with interlocking spaces. Axiality, symmetry, hierarchy, rhythm, repetition, datum etc. are ordering principles applied in the building. It is approached frontally from outside plaza. Configuration of the path inside is both linear and radial. Linear path from main pass terminates in a main space. Visual weight is achieved through massing, surface color and texture with good hierarchy among different scales. Load transfer is through spherical and right angled system. Wood, brick and stone are the structural materials used.

5.7. HAGIA SOPHIA : CONSTANTINOPLE (532 – 537 AD)

A Byzantine church, designed by Isodorus and Anthemois, was to act as a model for the vast architectural campaign by the emperor Justinian. It is rectangular in plan with huge domed space, relieving arches and arched colonnades. Forty clear storey windows through the base of the main dome lit the interior. The building is characterized by the massive appearance from



Plan



Sectional Geometry of Hagia Sophia by Benolt (Robertson 1963)

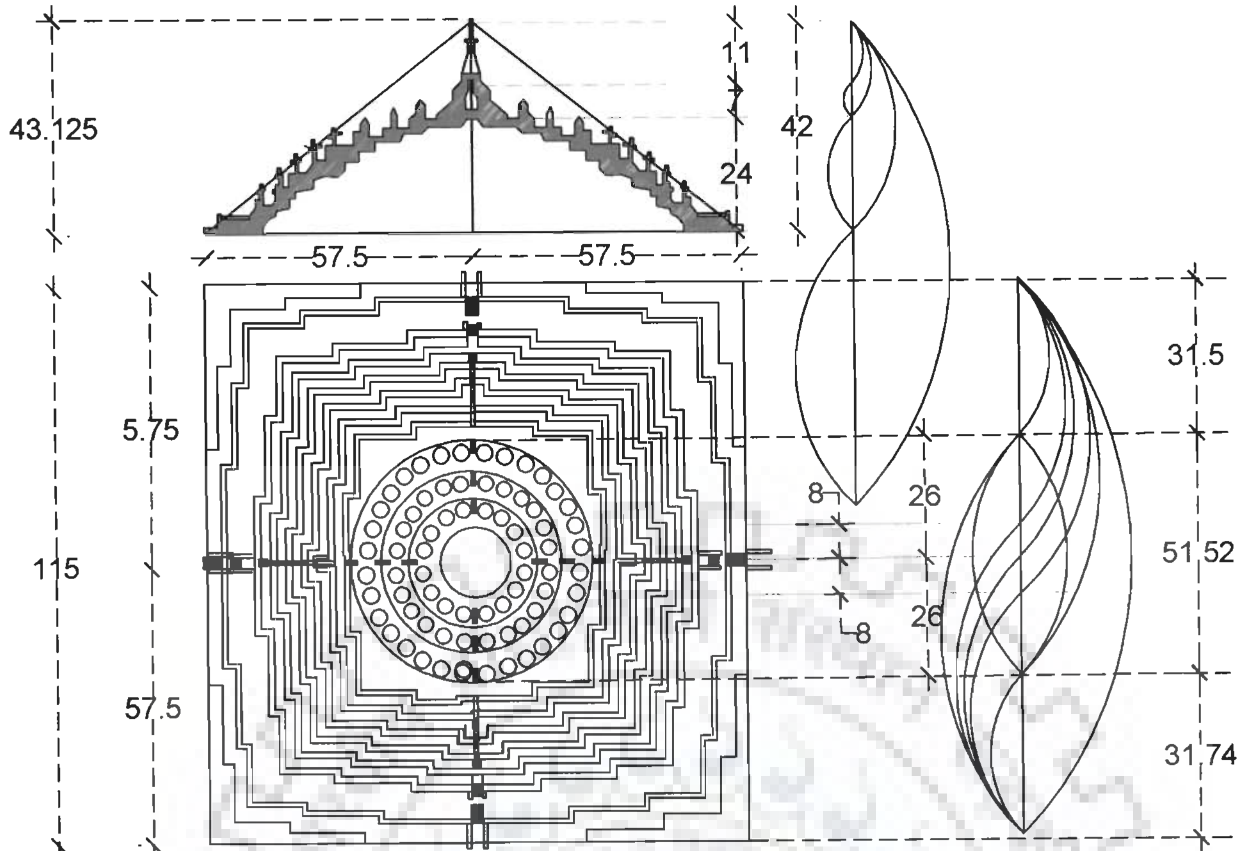
Fig 5.7 GEOMETRICAL ANALYSIS - HAGIA SOPHIA

outside with main dome flanked by semi-domes on two sides, and the colossal buttresses, while the richness of decoration marks the distinctness of the interior. The walls from ground up are embellished in identical manner. The spatial organization inside exhibits a perfect combination of longitudinal horizontal axis running from main entrance and terminating at the apse in the opposite direction and central vertical axis determined by huge dome.

The building has incorporated geometrical proportions in its organization fulfilling spiritual and aesthetic purposes. The form is strongly centralized around which other volumes are added. The interior spaces interlock with each other with main space surrounded by other spaces. All ordering principles are incorporated here. The building is approached frontally from outside with linear configuration of path, passing through different spaces terminate in a main space inside. The corners of the building are emphasized and order is creating through good inter-relationship of different scales. The structure has compressive system of loading with spherical load transfer. The building is regular and symmetrical hence safe from earthquake, though the first dome fell due to this reason but that was because of the shortcomings in its construction. Wood, brick stone and iron were the chief structural materials.

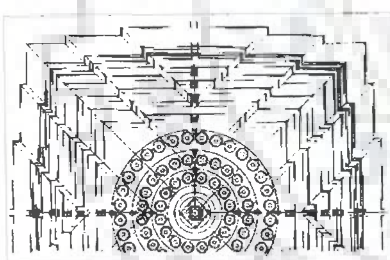
5.8. STUPA TEMPLE OF BOROBUDUR : JAVA (800 – 860 AD)

This stupa is based on the square mandala of Hindu origin explaining the origin of the world. It is a massive, symmetrical structure, 200 sq. meters in area constructed upon a low hill. Its basic shape is a stepped pyramid consisting of galleries and terraces with a stupa at the top. It has no interior space. It is based on a Buddhist cosmological model of the universe



All Dimensions Are In Meters

GEOMETRICAL ANALYSIS Doczi (1994)



Half Plan Showing System of Expanding Squares

Mandala Over Which Plan is Based

Fig 5.8 GEOMETRICAL ANALYSIS - STUPA TEMPLE OF BOROBUDUR

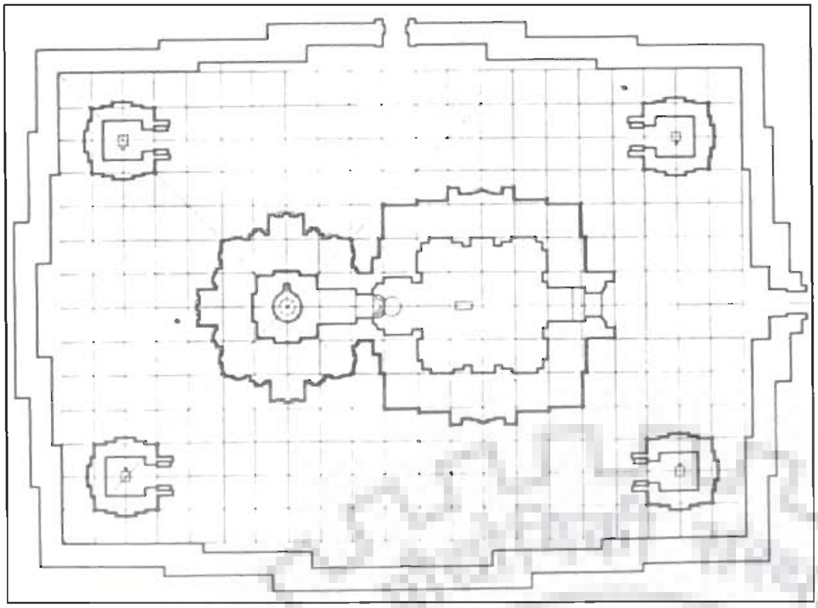
organized around Mount Meru. The lowest level is square in plan with approximately 112- 115 meter each side. The pilgrim ascending through six square terraces and three circular ones symbolically attains nirvanic state of absolute nothingness after crossing the world of desire. The six square terraces are embellished with richly decorated relief panels depicting Buddhist doctrines while the upper three circular ones have 72 grand bell shaped central stupa.

The composition is found to have incorporated mathematical proportions in the form musical ratios, strongly defined geometrical shapes in the form of circles and squares, and golden proportions in it. Religious symbolism and visual criteria are fulfilled through these geometrical systems.

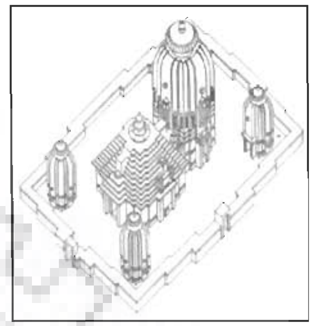
The form of the structure is regular with strong centrality. The movement galleries link all parts of the structure which converges as it goes up. Axiality, symmetry, hierarchy, datum, rhythm, repetition and transformation are ordering devices incorporated in the structure. It is approached frontally. The movement pattern is linear, paths pass through spaces, by spaces, finally terminating at the top near great central stupa. Massiveness of the structure, emphasized corners and richly decorated sculptures generate strong visual weight.

5.9. BRAHMESHWARA TEMPLE : BHUVNESHWAR (11th CENTURY)

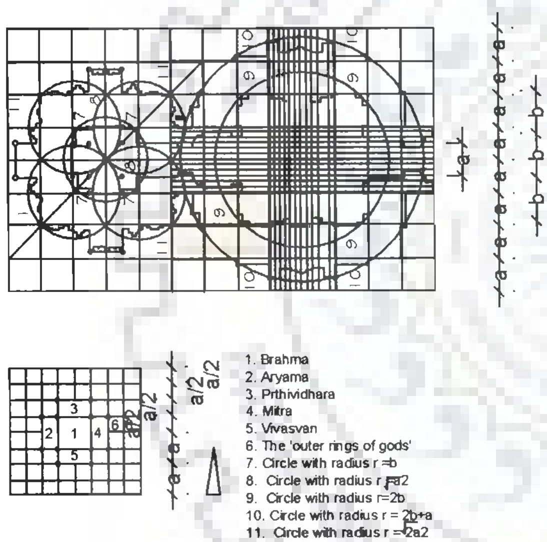
The structure is built on walled platform which supports the main temple with its four ancillary shrines. The platform is divided into certain proportions and all architectural members are incorporated in fixed alignments. It is divided into squares of 1.51 meter side. The point of diagonal crossing of lines leading from south–western and north - western corners



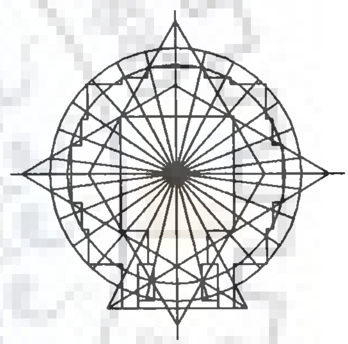
Plan



Axonometric View



Geometrical Analysis of Main Shrine



Geometrical Analysis of Ancillary Shrine

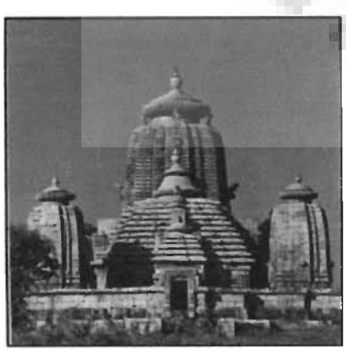
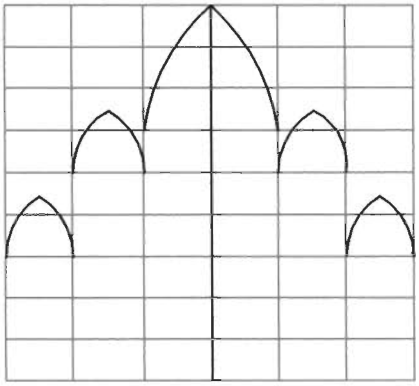


Fig 5.9 GEOMETRICAL ANALYSIS - BRAHMESHWARA TEMPLE
Volwahsen (1969)

determine the centre of the garbha-griha embellished with Load Shiva's symbol. The whole system is based on Vastu-Purusha Mandala containing 4 x 4 padas, laid out around the center of garbha-griha. The 'mukhashala' on the east has its own proportions based on the mandala. The building is symmetrical from north to south. The garbha-griha, the highest structure of the complex, and the mukhashala, having tiered pyramidical-type roof, meet at the deeply recessed splayed door through which the cella is entered. Geometrical proportions in the development of temple form are applied through the use of square and chronological divisions of the circle and module- based system in the form of padas of mandala determine the geometry of the structure. The spiritual and visual contents are achieved through this geometry. The form is regular, additive and linear. The approach to the building is frontal with linear configuration of movement from mukhashala to main cella. The rich sculptured surface, its color and the heavy massing determine the visual weight of the building. The structure is compressive in nature with transfer of load through right angled system. Regularity, symmetry and high material space ratio makes it safe from earthquake. Structural material used is stone.

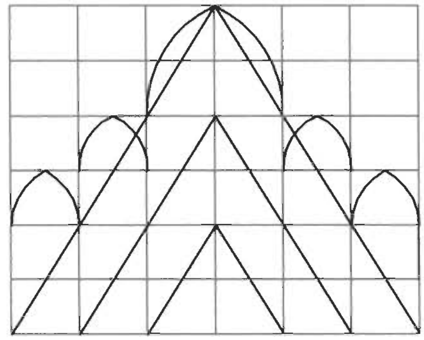
5.10. MILAN CATHEDRAL : MILAN (1385 – 1465 AD)

It is one of the largest cathedrals in the world. It was built on the site of ancient double cathedral which were replaced by this majestic building. The decision for this was taken sometime before 1386. The scale of the project was for beyond the experience of load architects and masons leading to unforeseen difficulties and the original designs was modified many times. In 1392, it was decided to build it according to 'ad-triangulum'. Shortly

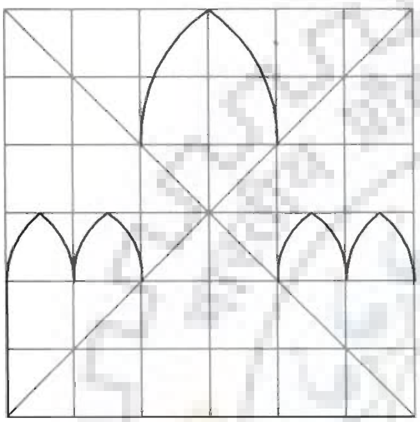


Section

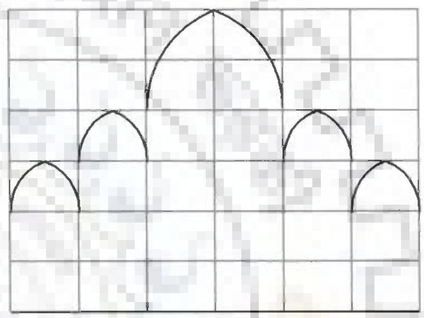
Proposal of Nicolas de Bonaventure, 1389
(Padovan ,2001)



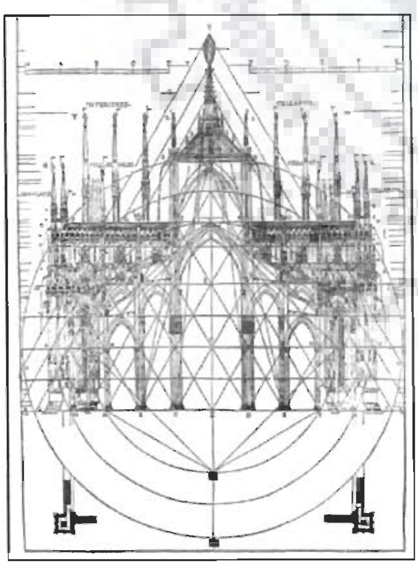
Section Of Milan Cathedral
by Annas De Firmburg, 1391
(Padovan ,2001)



Section of Milan Cathedral by
Heinrich Parler,1392
(Padovan ,2001)



Section of Milan Cathedral,
Final Proposal,1392
(Padovan ,2001)



Milan Section by Caesar Caesarino , 1521
(Ghyka ,1977)

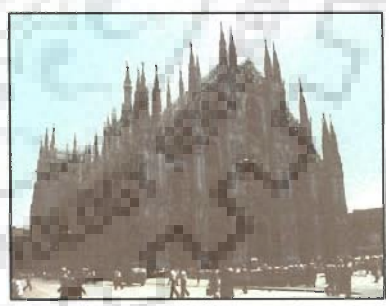


Fig 5.10 GEOMETRICAL ANALYSIS - MILAN CATHEDRAL

afterwards, the design was changed to 'ad-quadratum'. According to Wittkower (1953) [83], by that time the construction had already been started according to 'ad-triangulum' and was continued up to the piers of aisles. In both the schemes, the elevation seemed too high. The council decided to switch over to another geometrical method. Keeping the lower part, the design of the upper part was modified with the help of 3-4-5 triangle and the overall height was brought down. Ghyka (1977) [31] reproduced the elevation of the dome of Milan cathedral originally published in 1521 by the architect-in-charge of the dome Caesar Caesariano. Ghyka mentions that this diagram shows the function of concentric circles and the use of $\sqrt{3}$ proportion in the geometry of the building. The proposals tendered by various architects are shown in the figure.

The cathedral is a mass of white marble over the brick core, with lofty traceries windows, forest of pinnacles crowned with statues. The cathedral has a cruciform plan with monumental interior. The capitals were treated like niches with full scale statues of humans around each column.

The different parts of interior are based on multiples of the fixed module of one bay of the aisle. These proportions created desired monumentality and visual qualities.

The form is centralized, additive and linear in nature. Different spaces are linked by common space. The presence of all ordering principles can be noted here. The building has frontal approach from outside with the configuration of internal path as linear, passing through spaces, terminating in apse. The articulation is of very high quality. The structure is compressive in nature with spherical load transfer system. Natural light is achieved through walls and roofs directly and indirectly.

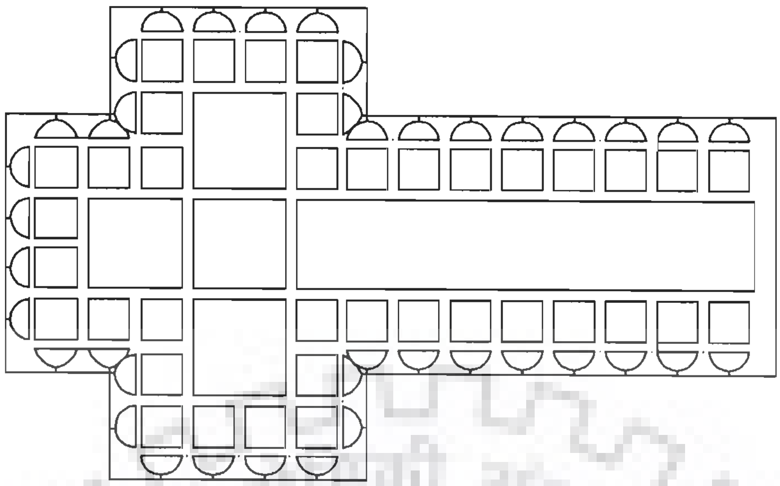
5.11. S. SPIRITO : FLORENCE (1436 – 1482 AD)

A centralized basilican church by Brunelleschi, it has domed crossing from where emanate three equal arms with longer nave. The side chapels are in the form of niches which were made to be seen as protrusions from outside. These niches also acted like modules on the basis of which the composition of the building is completed. The use of mathematical and geometrical proportions is also very prominent in this building.

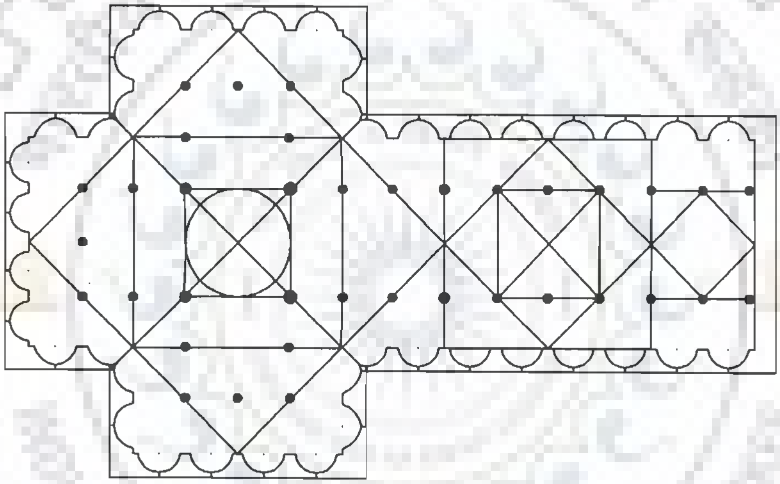
The form thus results from the addition of modules, having dominant center and overall linearity. All the spaces are linked by common space of the nave. The approach to the building is perpendicular to the front façade with linear configuration of path inside terminating in the main space of chapels opposite the frontal entrance. The mass of the building adds to it visual weight. The structure is both compressive and tensile in nature with load transferring through spherical system and trusses. Regularity and symmetry of form makes it safe from earthquake.

5.12. VILLA CAPRA : VICENZA (1569 AD)

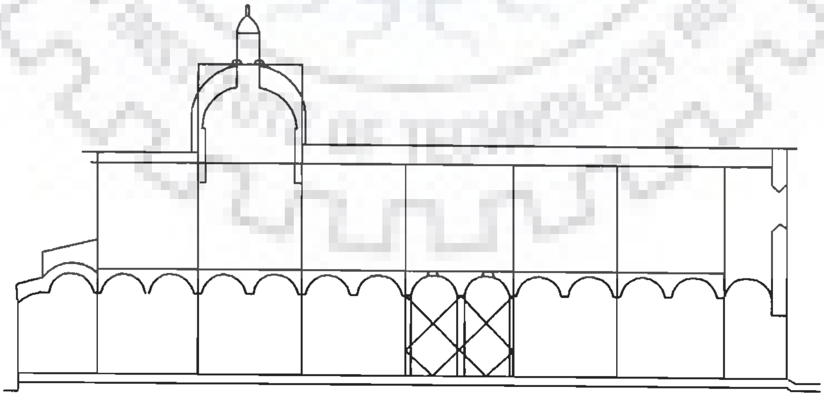
Designed by Andrea Palladio, completed by Vincenffarzo Scamozzi, the building is completely symmetrical with centralized square plan and four loggias on all four sides relating to the landscape outside. The central domed space is the main feature from where it got its name. It has a pedimented temple front. The northwest loggia is recessed into the hill above an axial entry from the front gate. This axis continues visually to the chapel situated at the edge of town thus relating the building with the town. Under the floor of the



Modular Plan

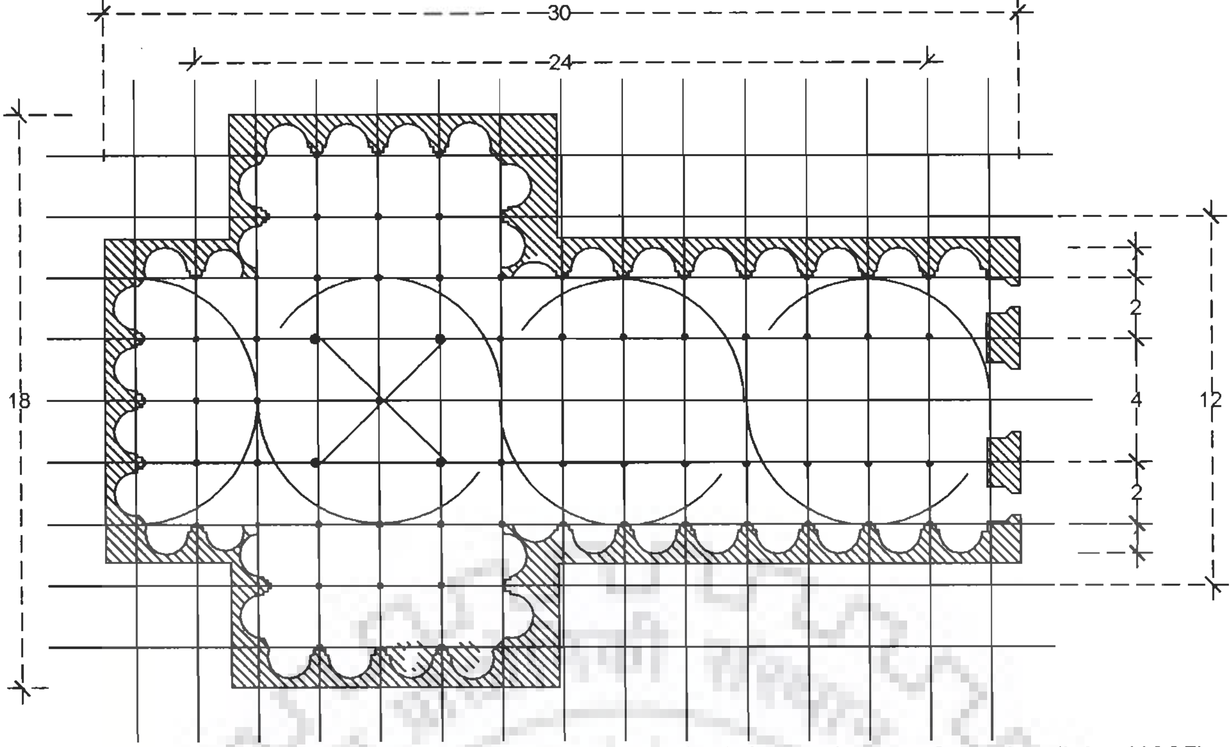


Plan



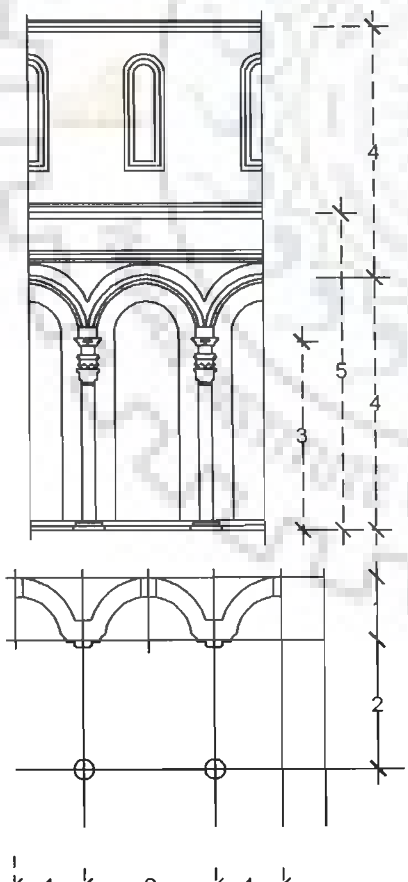
Longitudinal Section

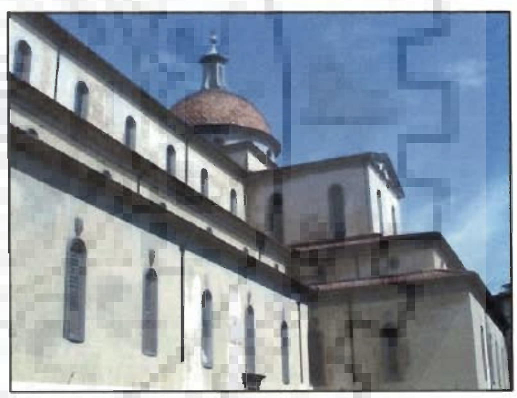
Fig 5.11 (a) GEOMETRICAL ANALYSIS - S.SPIRITO
Clark & Pause (1996)



All numerical dimension are from Joedicke (1985)

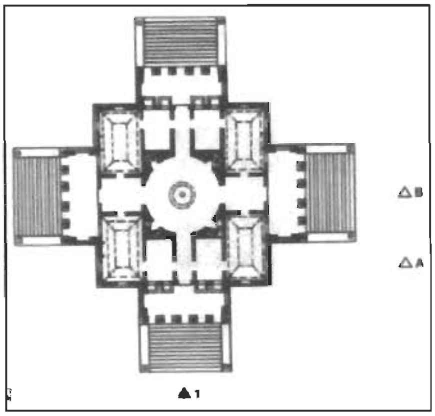
Plan Robertson (1963)



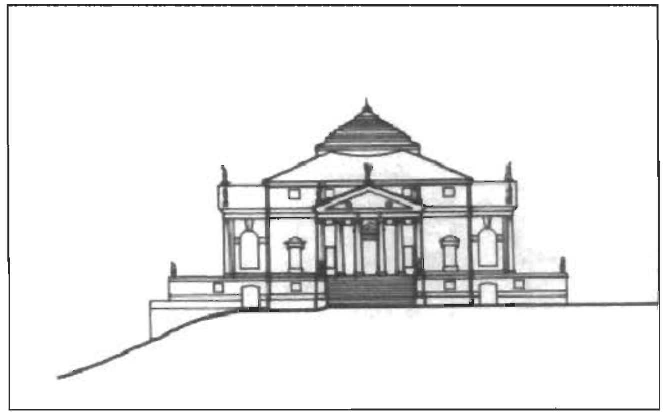


Sectional Detail Joedicke (1985)

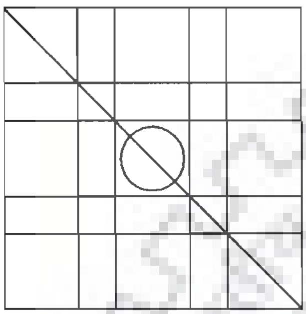
Fig 5.11 (b) GEOMETRICAL ANALYSIS - S.SPIRITO



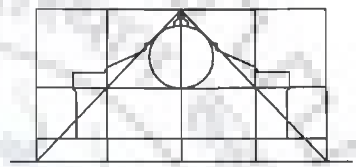
Plan



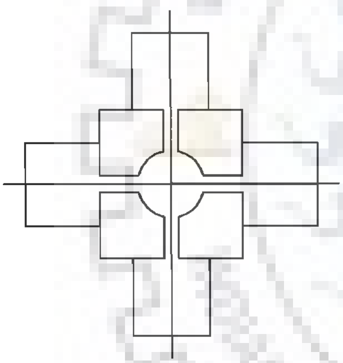
Elevation



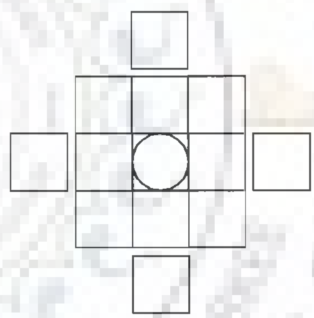
Plan Geometry



Section Geometry



Symmetry



Disposition of Square units

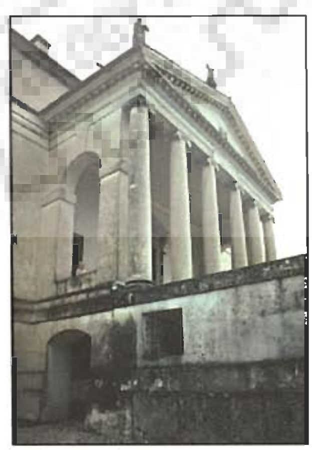


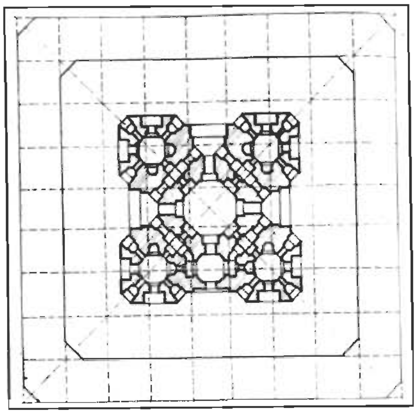
Fig 5.12 GEOMETRICAL ANALYSIS - VILLA CAPRA
Clark & Pause (1996)

loggias and hall there are rooms for family and conveniency. Palladio used mathematical proportions in the design of the spaces. Geometrical figures of square and circle were predominantly used in the composition to give it a desired visual quality. Regular forms were added with dominant centrality. The spaces are linked by common space. Approach to building is frontal with radial internal movement.

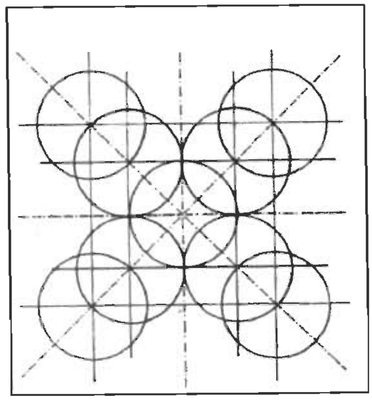
The structure has both compressive and tensile loading pattern. Load is mainly transferred through spherical system but wooden trusses are used in loggias. Its form makes it safe from earthquake forces. Natural light enters directly through walls and indirectly through roof.

5.13. HUMAYUN'S TOMB : DELHI (1585 AD)

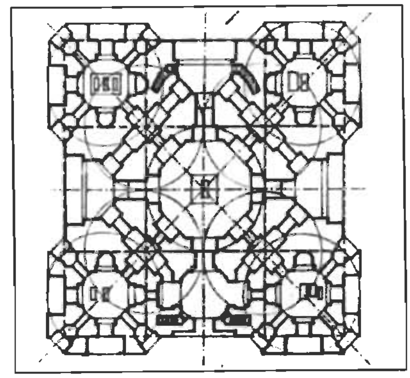
This work was carried out under the direction of Mirak Mirza Ghiyas, a Persian architect. It is, therefore, entirely Persian in its conception and planning, based on concept of 8 paradises; it is situated on the west bank of river Yamuna. There is a great square enclosed garden around the mausoleum. The garden is entered on the middle of west and south sides with four central avenues dividing the vast garden into four quadrants. The mausoleum in the central square rises from a high plinth which in turn, has a low stone base. The tomb structure consists of central octagonal double-domed chamber containing emperor's cenotaph, the four corner chambers with four 'iwans' (monumental arched niche or porch) between them. The spaces are linked by passages running diagonally and orthogonally on a pattern determined by grid. The other rooms around central chamber have shallow vaults.

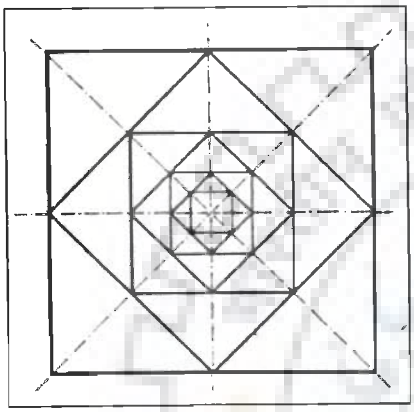


Plan Showing Platform of 81 Square on Which Mausoleum Stands

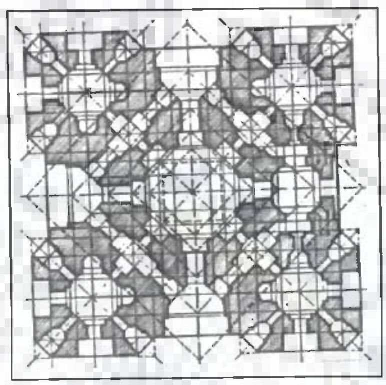


The Basic Organization of The Plan

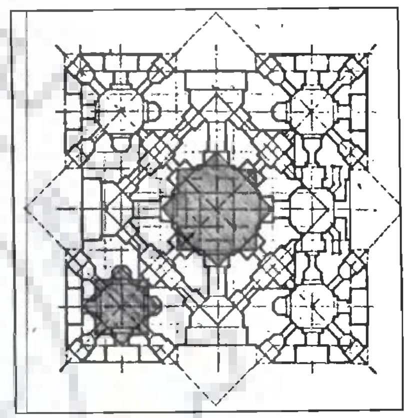




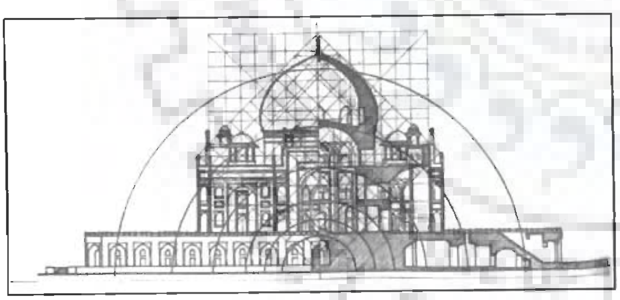
Expanding Squares Forming Ratio Of Two

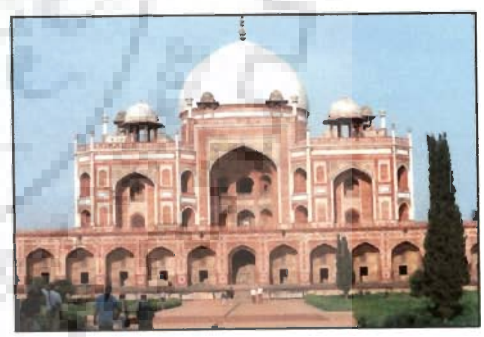


The Main Grid Lines Delineating The Passages in The Plan

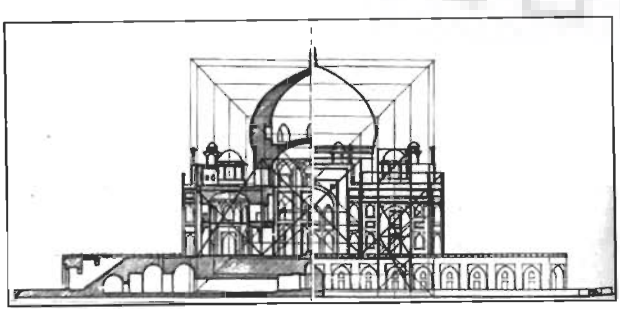


Rotation And Transformation of Basic Square





Elevational Geometry



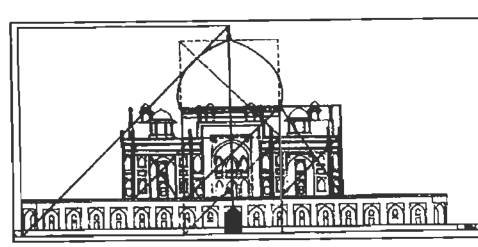


Fig 5.13 GEOMETRICAL ANALYSIS - HUMAYUN'S TOMB
Minakshi Mani (1989)

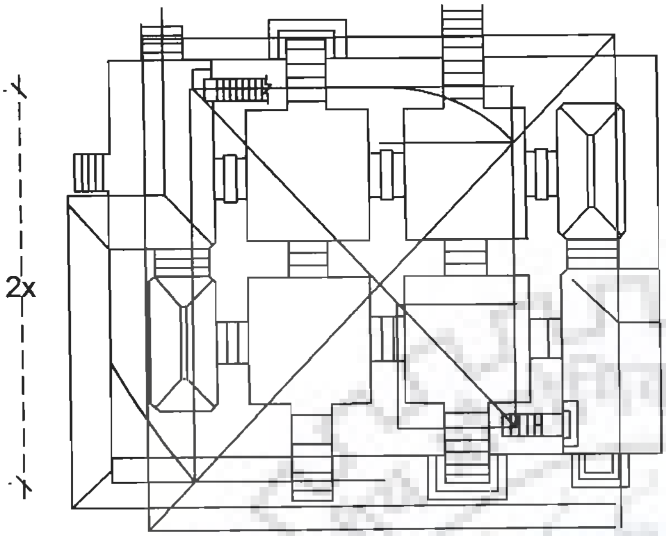
The varied and multiple decorative patterns express the different aspects of principle of Unity. Arches, chattris, stone screens articulate the form and linear bands around openings articulate the facades. Geometrical proportions in the form of side of the square to its diagonal to create 'pattern-plans', golden proportions, modularity in plan pattern and regulating lines determine the architecture of this building.

Golden section was used in the ordering and articulation of the pattern while regulating lines control the proportions of façade. Square is the leitmotif in the whole composition. The geometry here expresses spirituality and also fulfills aesthetic criteria. The form is regular and centralized comprised of addition and subtraction of volumes in it. The spaces are linked by two different patterns of movements. The configuration of path is radial-centrifugal as well as centripetal. The movement routes pass through spaces, by spaces terminating in main space. Form and façade articulations are of very high quality. The structure is compressive and the load predominately transfers through spherical system. Regularity, symmetry and exceptionally high material/space ratio makes it safe from earthquake.

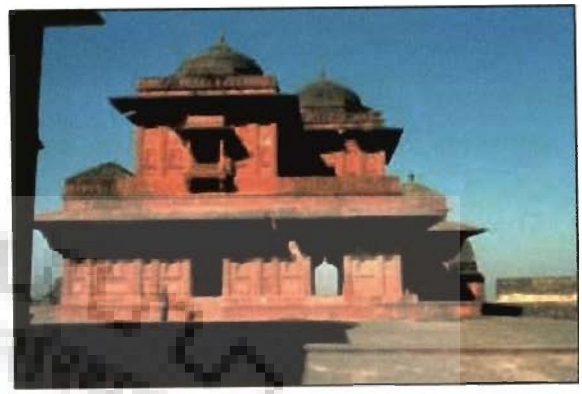
The material used was dressed stone, rubble masonry, brick and wood. The dome is built up of brick and mortar. The base, plinth and main structure is built up of rubble masonry.

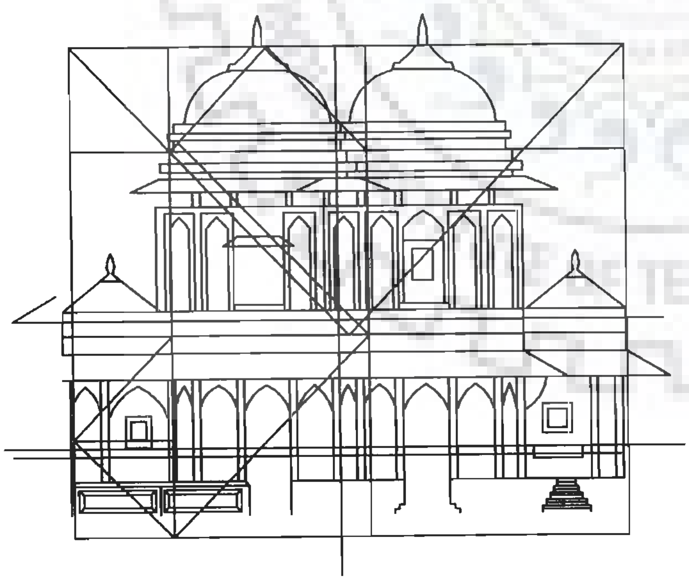
5.14. BIRBAL HOUSE : FATEHPUR SIKRI (1569-74 AD)

This extremely beautiful building is located of the north-west corner of the royal complex overlooking Elephant Gate. It consists of four interconnecting rooms and two entrance porticos one on either side of rectangular plan. It is built in red sandstone. The construction is trabeate with

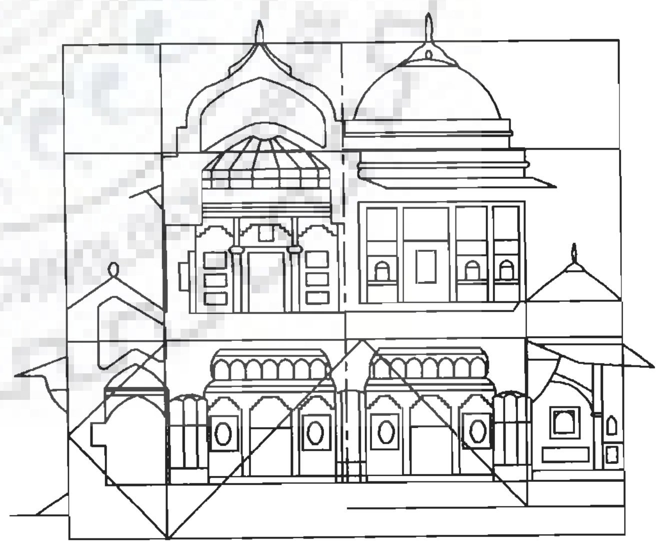


Plan





Elevation



Section

Fig 5.14 GEOMETRICAL ANALYSIS - BIRBAL HOUSE
Navin Gupta (1986)

pillars and lintels with the use of highly carved brackets for reinforcement and for aesthetic purpose. Ground floor rooms have flat ceiling while the upper rooms have domed ceiling with ribs and panels. The domes are based on octagonal drums. The two small rooms on the ground floor adjacent to the two porticos on either side have 'chhappar' ceiling which culminate in pyramidal roofs on first floor.

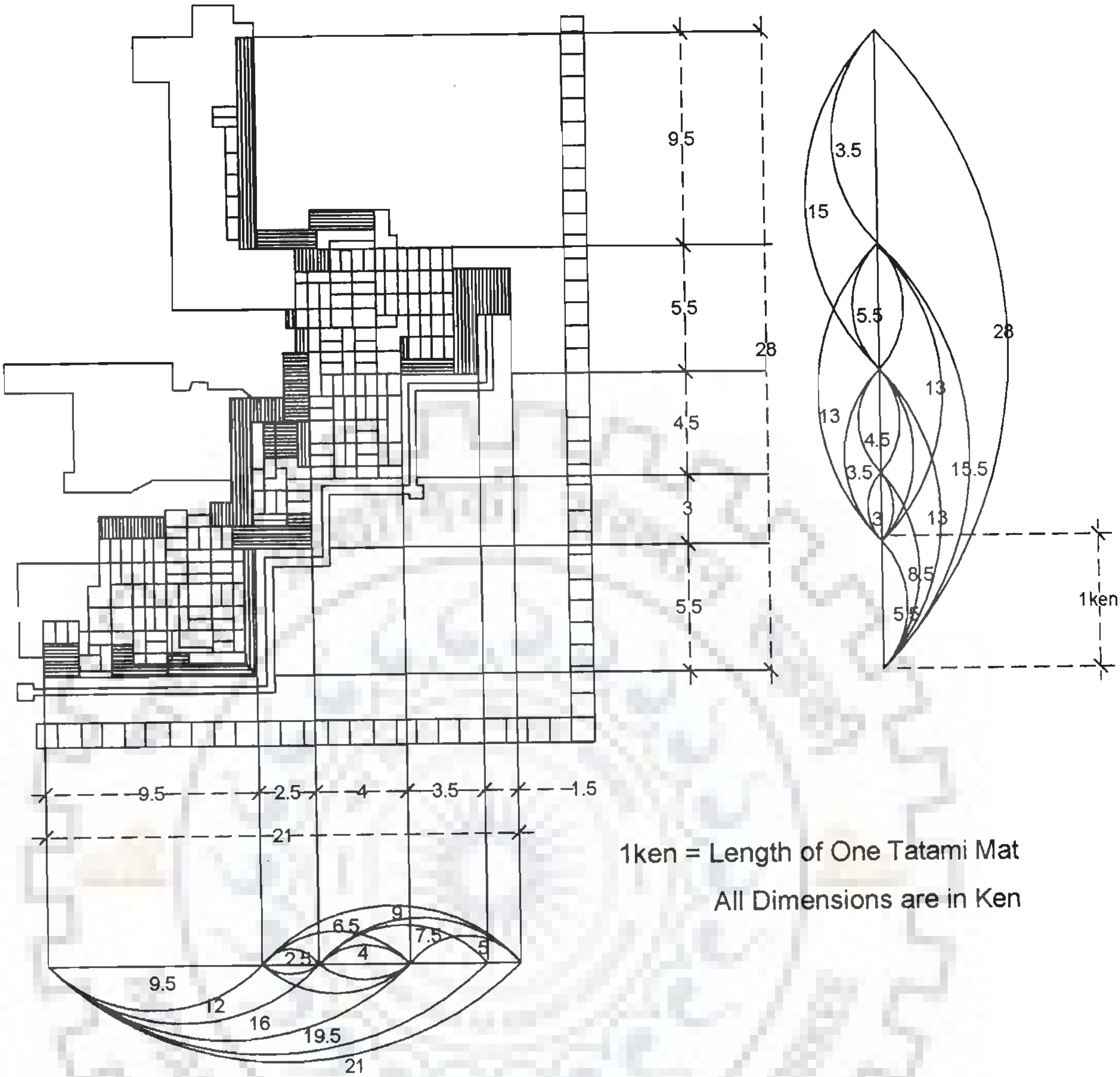
The molded three tired brackets support the wide and slanting projection continued on all sides. Surface carving in incised, low and medium reliefs embellish the interior as well as exterior.

The building inherits geometrical proportions along with the use of regulating lines in its composition for aesthetic reasons and for the creation of desired mughal character. The parts are added on grid organization to create form. The building is approached from two sides and the movement inside goes through main spaces.

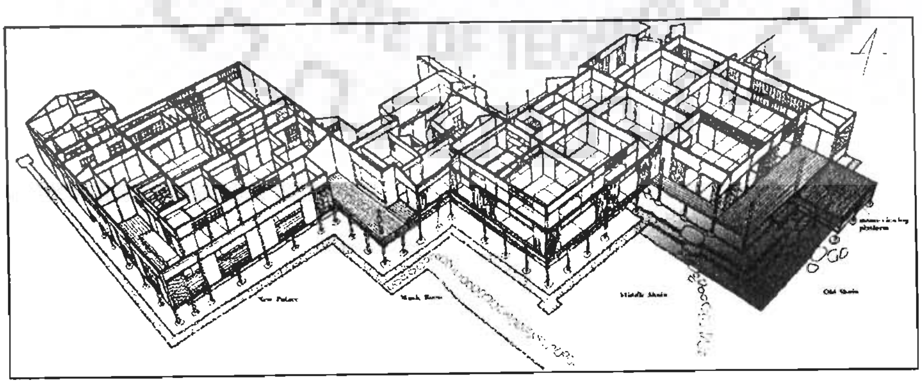
The building has emphasized corners with strong visual weight due to massing, surface color, texture and optical patterns on the exterior surfaces. It is built both on visual as well as human scale to create order with good co-operation among parts of different sizes. Natural light direct and diffused enters through walls.

5.15. KATSURA PALACE : KYOTO (1620 – 60 AD)

Designed by Prince Toshihito, it is the finest piece of secular, domestic architecture. Meant to be used between spring and autumn, it was more like a summering place. The individual parts of Katsura faced 19^0 southeast to get the perfect view of harvest moon just rising above the horizon and full sunlight during the four seasons with cool breeze in summer. The gardens are

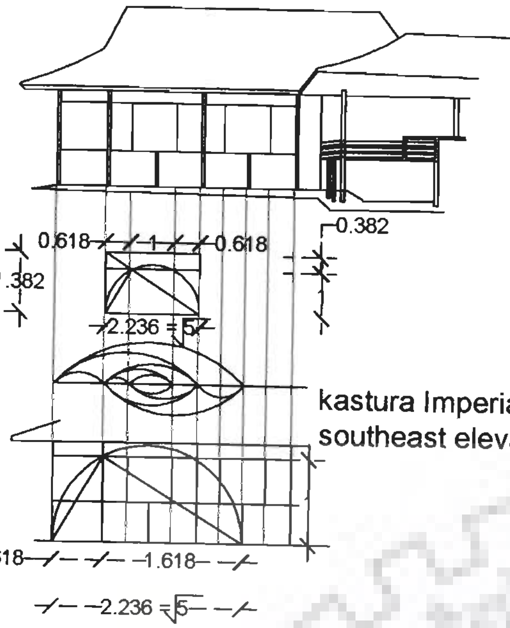


GEOMETRICAL ANALYSIS
Doczi (1994)

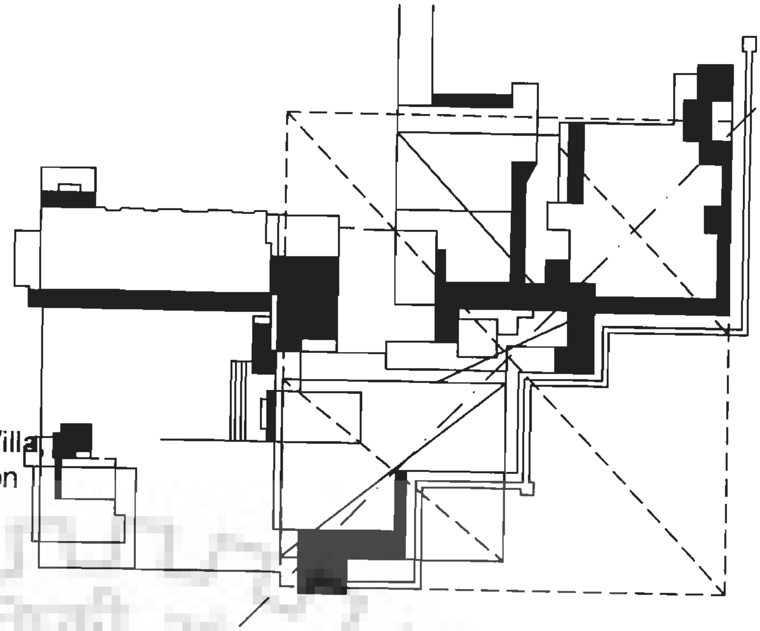


Isometric View Showing Modular Planning

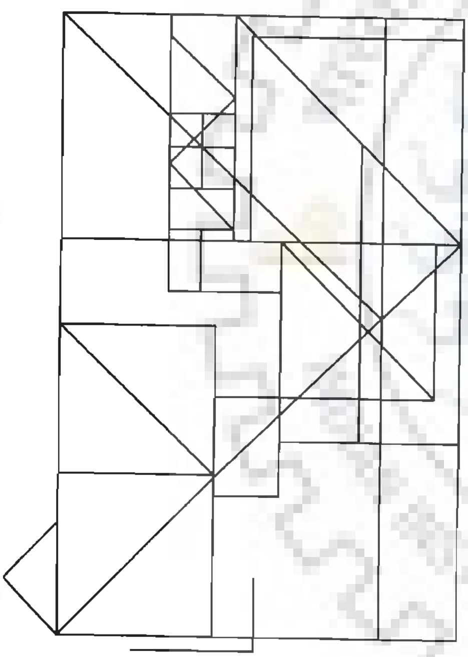
Fig 5.15 (a) GEOMETRICAL ANALYSIS - KATSURA PALACE



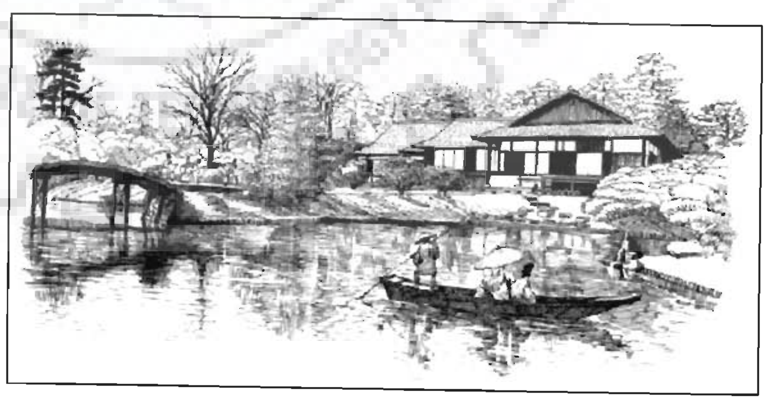
Geometry of Part Elevation
Doczi (1994)



Geometrical Basis of Partial
Spatial Organization
Navin Gupta (1986)



Geometrical Organization of
Plan Through Regulating Lines
Navin Gupta (1986)



View From the Lake

Fig 5.15 (b) GEOMETRICAL ANALYSIS - KATSURA PALACE

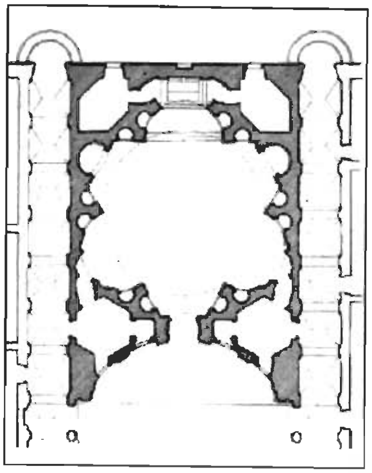
carefully arranged around artificial lake. The moon reflected in the pond with the palace had a space exclusive for this view. The construction is of light wood timber frame using triangular trusses with tile roofs. Building is dimensioned according to modular tatami layout, with the space in multiples of tatami used on floors in all cases. Wood was left plain occasionally even retaining its bark. Walls are also lacking intricacy. The building exhibits an intimate scale.

Apart from modularity, mathematical and golden proportions are also incorporated along with the use of regulating lines in the organization of composition and for functional criteria.

The form is clustered and additive in nature. The spaces are placed adjacent to each other without any hierarchy and symmetry. The approach is frontal with linear configuration of movement pattern inside the structure. The movement is from one space to another without any defined circulation path. The corners of the building are emphasized. The visual weight is due to surface texture, color and optical patterns formed on the outer walls. The structure is compressive with load transfer through non-rigid right angled and diagonal truss systems. Stone was also used as structural material in outer walls. Natural light enters through walls directly, indirectly and in diffused form.

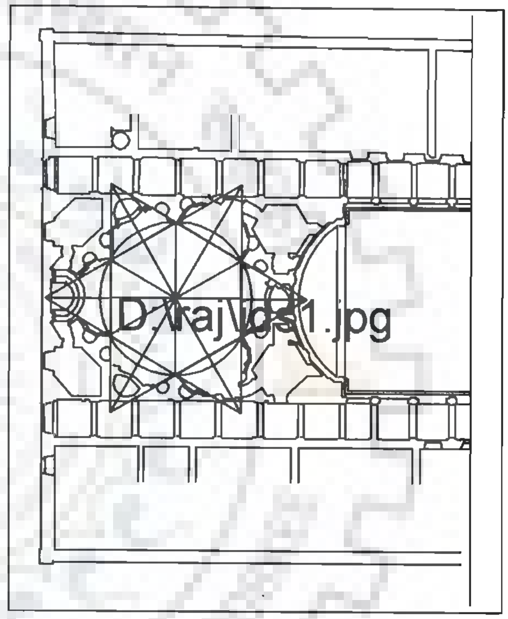
5.16. S. IVO DELLA SAPIENZA : ROME (1642 – 50 AD)

Begun by Pirro Ligorio and continued by Giocommo Della Porta, it is situated at the end of courtyard of Palazzo Della Sapienza. Its plan consists of two interlocking triangles forming six pointed star whose ends are alternately convex and concave curves. The form has strong symbolism referring to the

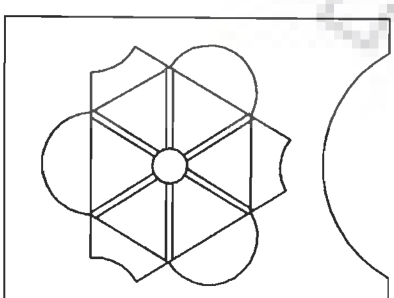


Plan

Section



Geometrical Analysis
Giedion (1956)



Geometrical Analysis
Joedicke (1985)

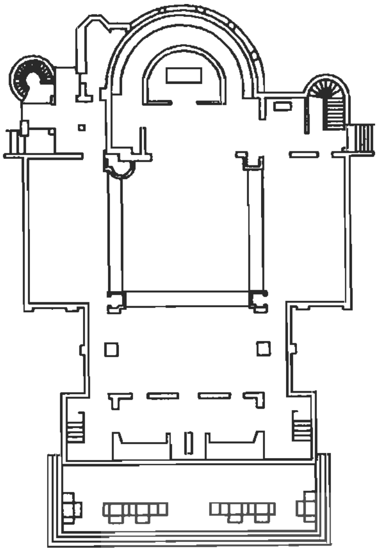
Fig 5.16 GEOMETRICAL ANALYSIS - S.IVO DELLA SAPIENZA

star of wisdom. The pilasters continue upwards till the molding of the dome. The star plan is retained with the dome finally transforming into circular oculus above, on which stands the lantern. The church is a complex whole derived from the manipulation of simple geometrical forms. The wall surfaces of the interior are kept monochromatic to emphasize the articulation of surfaces.

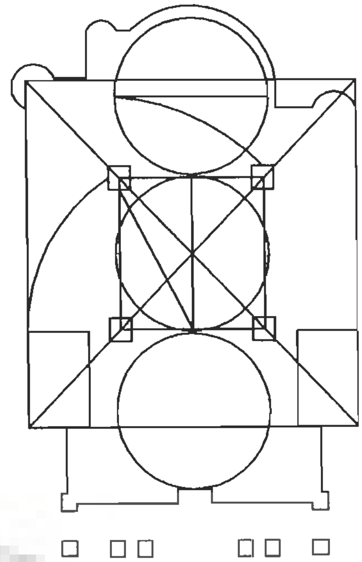
The form is simultaneously regular, additive, subtractive and centralized. Rhythm is achieved in composition through symmetry, repetition and transformation of parts. The building is approached frontally with radial movement inside though the size is very small. The visual weight is achieved through massing, optical patterns and texture of the surface. The structure is compressive is nature which spherical load transmission system. The structural and non-structural parts are effectively integrated with each other. Stone is used as a structural material. Natural light enters in direct as well as diffused form from roof and directly from wall surfaces.

5.17. TRINITY CHURCH : BOSTON (1872 – 77 AD)

It was designed by Henry Hobson Richardson in Romanesque style of southern France. It consists of latin cross plan. The central tower is low and wide emphasizing the centrality of the building. Granite is the main building material. The tower has immense weight. A space 90 feet square was reserved for tower foundation. The building is situated on a wet filled marshy land. The foundation of the tower was built with wooden piles with the use of concrete to prevent lateral movement. The tower is actually supported on piles. Four granite pyramids on top of piles support the corner piers of the tower.

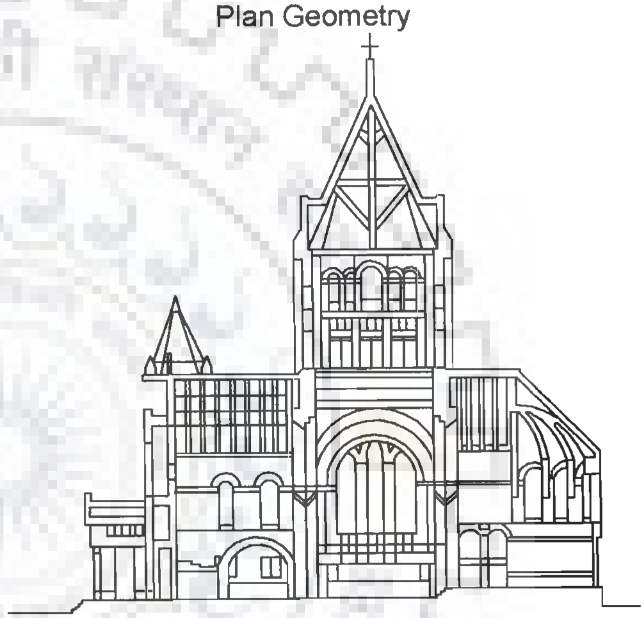


Ground Floor Plan

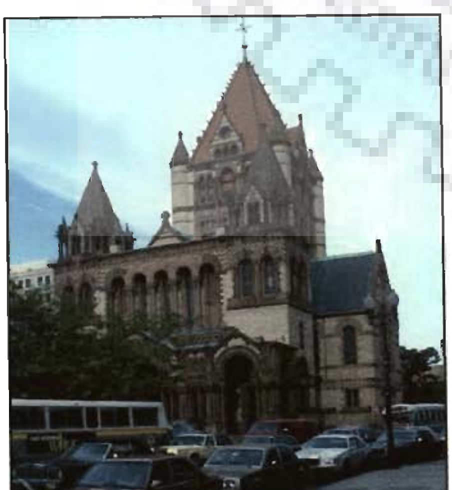


Plan Geometry

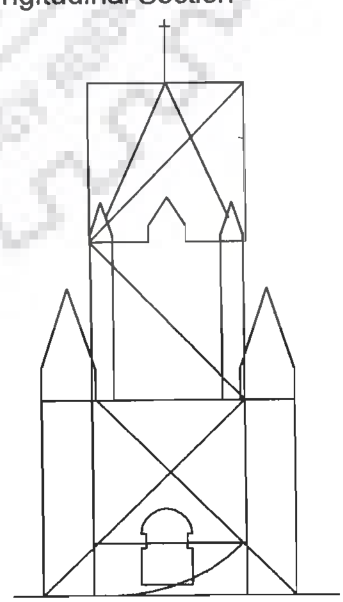
Elevation



Longitudinal Section



Plan



Rear Elevation Geometry

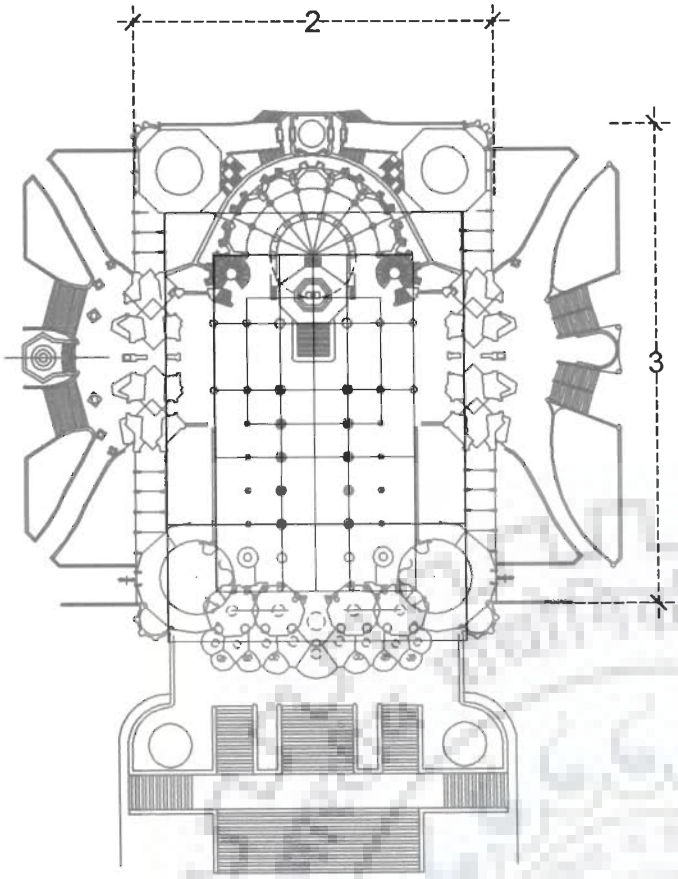
Fig 5.17 GEOMETRICAL ANALYSIS - TRINITY CHURCH
Clark & Pause (1996)

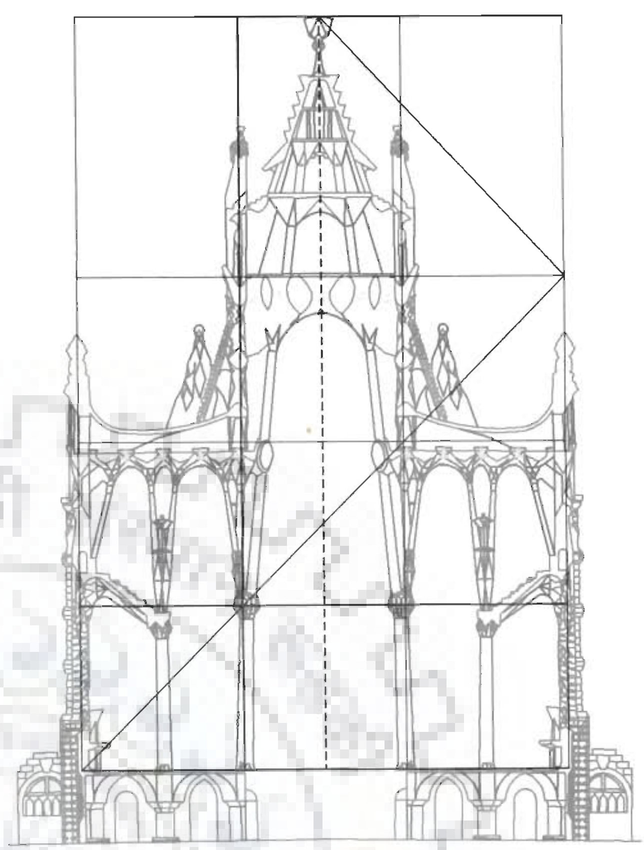
The building is characterized by strong geometric order because of the application of golden and geometrical proportions in its organization. The form is regular and additive with dominant centrality. The spaces are placed adjacent to each other and at some places interlock with each other. The building front three streets so can be approached both frontally and obliquely. The movement pattern inside terminates in the apse while passing through main nave space and going by secondary spaces. The load transfer is through diagonal truss system at some places and through and spherical system at others. The regularity and symmetry of form makes its safe from forces due to earthquake. Natural light is achieved directly and indirectly through walls.

5.18. SAGRADA FAMILIA CHURCH : BARCELONA (1890 AD)

It is Antoni Gaudi's most famous work which left unfinished due to his death. It was intended to represent a complex system of symbolisms and visual explication of truth. He designed facades representing the various phases of Christ having 18 towers representing different symbolisms with tower of Christ as the tallest one. It was planned on the basis of gothic basilica with five naves, an apse, transept and ambulatory. The work continued in different phases after his death, the last additions were made between 1954 and 1976 completing façade and four western towers.

Apart from geometrical proportions, the building exhibits mathematical proportions in overall dimensions of plan as well as of section. It also incorporates modular system based on the multiples of one aisle bay as single module. The church was intended to represent 'twentieth century cathedral' having monumental scale in its form. It is predominantly centralized





Plan Geometry

Section Geometry

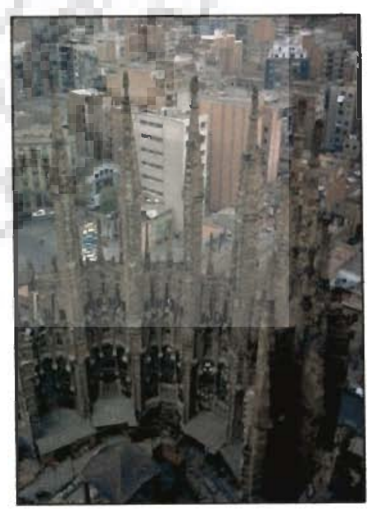


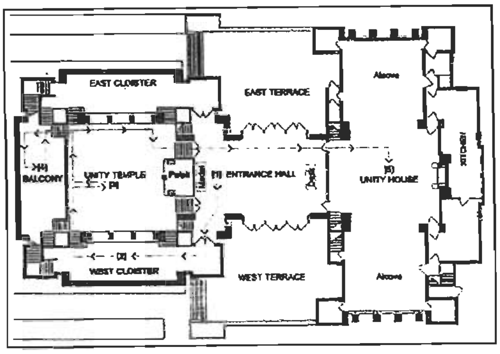
Fig 5.18 GEOMETRICAL ANALYSIS - SAGRADA FAMILIA CHURCH
Navin Gupta (1986)

in its form and spatial organization. The spaces are placed adjacent to each other while at some places they interpenetrate. The building was designed to be approached from three sides with internal movement pattern as linear in configuration. It has strong visual weight due to intense surface articulation and overall massing with good relationship between hierarchies of scales. The structure was intended to be compressive in nature with load transferring through spherical system. Despite explicit variations the building is regular and symmetrical in plan and in elevation thereby ensuring safety from earthquake forces.

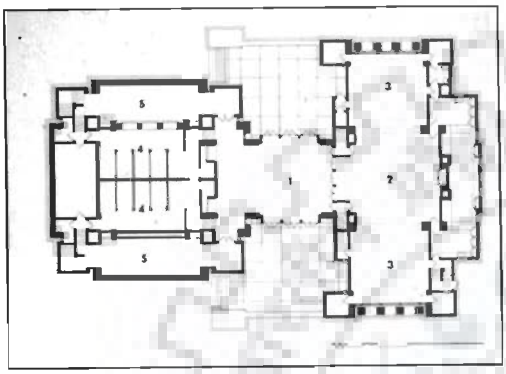
5.19. UNITY TEMPLE : ILLINOIS (1908 AD)

Designed by Frank Lloyd Wright, it resulted in a sacred space with introverting central rooms. The building has solid walls made up of RCC. The scale is at once monumental and intimate, representing high level of spirituality. Exposed concrete was used to emphasize and define mass and volume from outside. Floating planes define interior spaces.

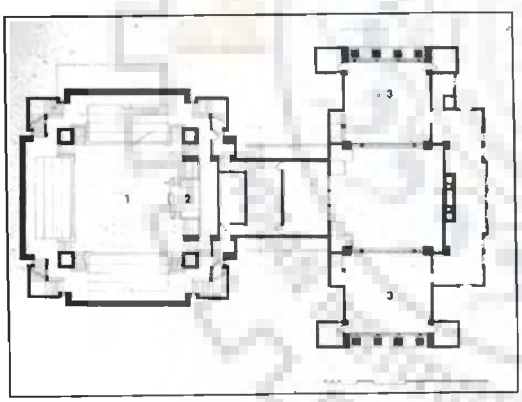
The geometrical proportions are predominantly applied in this twentieth century church for spiritual symbolism along with aesthetic and functional reasons. The form is additive with different masses clustered around each other. The spatial organization is radial and clustered with important spaces enclosed within larger space. The building is approached frontally and obliquely with linear configuration of path inside terminating in a main space. The form is articulated through emphasized corners. The structure is flexural in nature with non-rigid right angled load transfer system. Being regular and symmetrical it is safe from earthquake forces. Natural light enters inside directly through walls and roof.



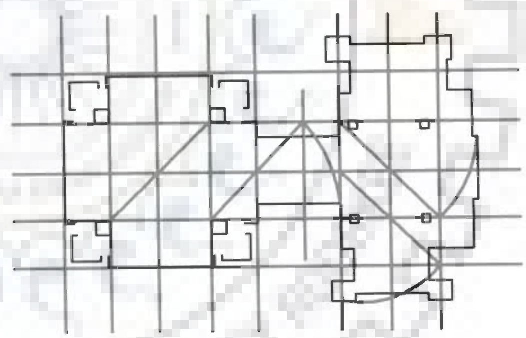
Ground Floor Plan



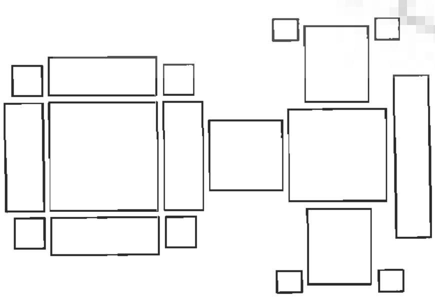
First Floor Plan



Second Floor Plan



Plan Geometry



Disposition of Figures

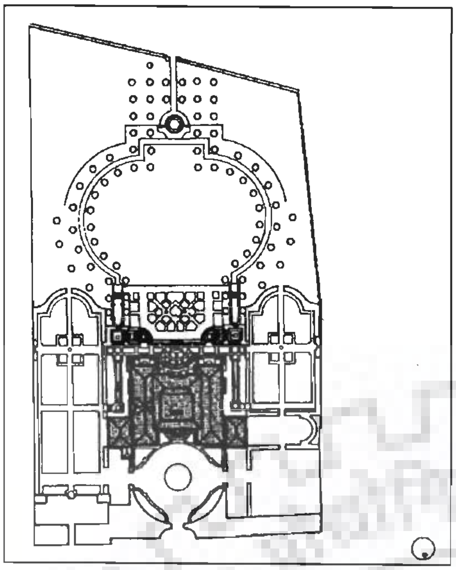
Section Geometry

Fig 5.19 GEOMETRICAL ANALYSIS - UNITY TEMPLE
Clark & Pause (1996)

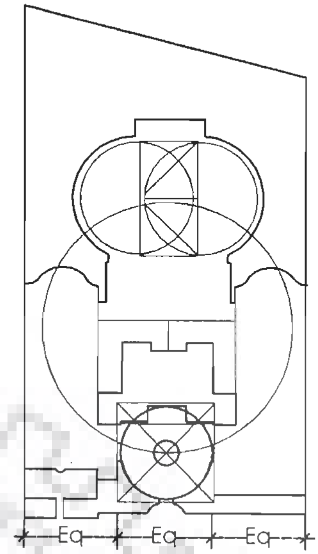
5.20. HEATHCOTE : YORKSHIRE (1906 AD)

Designed by Edwin Lutyens, this villa occupies a sub-urban site of 04 acres. The plan is dramatic, blocking the central axis within the house, forcing the visitor to take circuitous route. The spatial experience is full of contrasts and surprises. The geometry of the house is continued to the stepped gardens. The overall organization consists of pyramidical composition of horizontal planes created through the terracing of the site and the treatment of the house. It is built up of yellowish local stone, with grey stone dressings and red pan tiles. The characteristic feature is the play of Doric pilaster sunken into rusticated walls which according to Lutyens enhance the scale greater than the height of the rooms permitted.

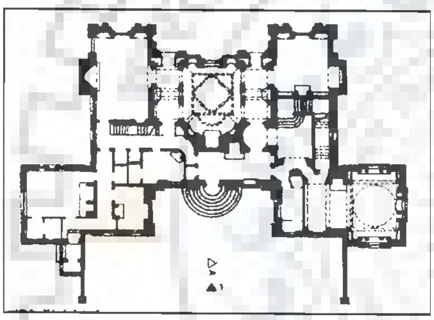
Geometrical proportions are found to exist in the composition for aesthetic and functional purposes. The form is a combination of additional and subtraction of masses making clustered composition emphasizing centrality. Various spaces are linked by common circulation space. The building is approached frontally with linear configuration of movement inside it. Path passes by spaces thereby linking them and at some places, pass through them. The corners of the building are emphasized. It has strong visual quality because of massing and surface articulation with good relationship among different scales. The structure is compressive at some places, tensile and also flexural at other parts with load transmission predominantly through right angled and diagonal truss system. The building is safe from earthquake forces because of its regularity and symmetry. It receives natural light directly through walls.



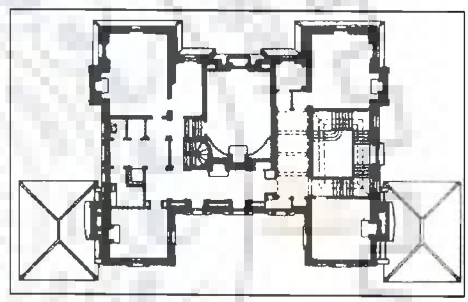
Site Plan



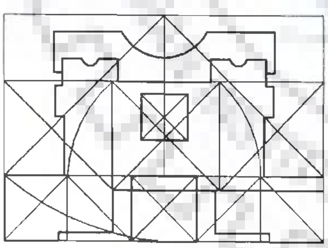
Geometrical Analysis



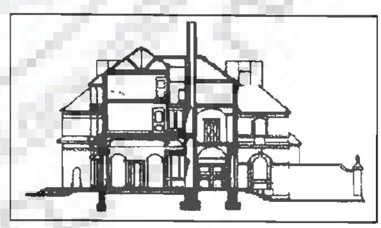
Lower Floor Plan



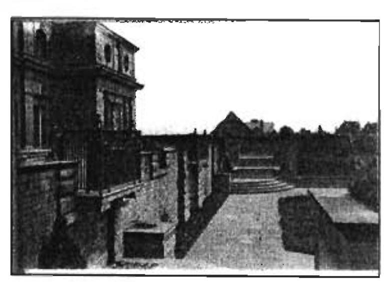
Upper Floor Plan



Plan Geometry



Section



Elevation

Fig 5.20 GEOMETRICAL ANALYSIS - HEATHCOTE
Clark & Pause (1996)

5.21. NATIONAL FARMER'S BANK : MINNESOTA (1907– 08 AD)

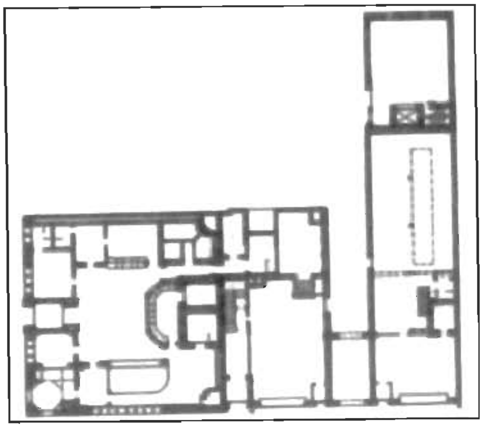
One of the finest pieces of Louis Sullivan, it consists of main single banking room in a cubical space enhanced from outside by a wide stained glass lunette windows and corbelled brick cornice. The base is of red sand stone with dark red brick walls. Offices and shops are accommodated in separate block at the rear. The façade has great vaulted window in the walls with rows of dark square windows puncture the base.

The building incorporated mathematical and geometrical proportions in their organizations in plan and elevation for aesthetic and functional purpose while ornamental pattern strike golden rectangles. The form is regular and additive in nature forming clustered spaces. Different spaces are linked through common circulation space. The approach to building is frontal with linear configuration of path inside. The corners are emphasized. Visual weight is due to mass of the bank cubical along with surface articulation. The structure is compressive with right angled and spherical load transmission. Wood is also used in roofing as a structural material. Natural light enters directly through walls and in diffused form through roof.

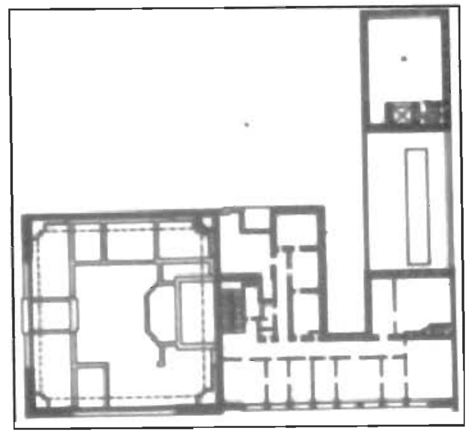
5.22. WOODLAND CHAPEL : STOCKHOLM (1918 – 20 AD)

Funeral chapel designed by Erik Gunner Asplund, It is a small building with hipped roof on timber columns having domed space inside. The approach leads to the main room supported by 12 columns having domed roof inside for gathering of mourners. The building is very simple volume with grayish white walls and black shingle roof.

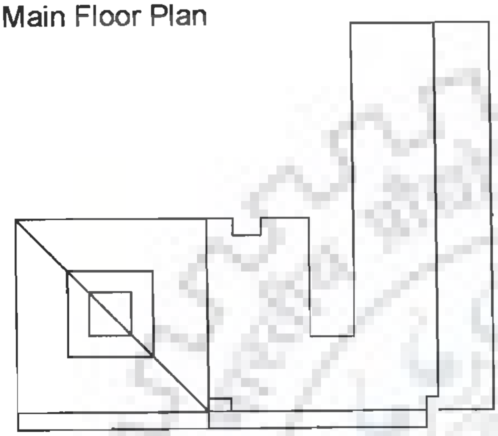
The building incorporates mathematical, geometrical and golden proportions for timeless and aesthetic quality. The form is regular and additive



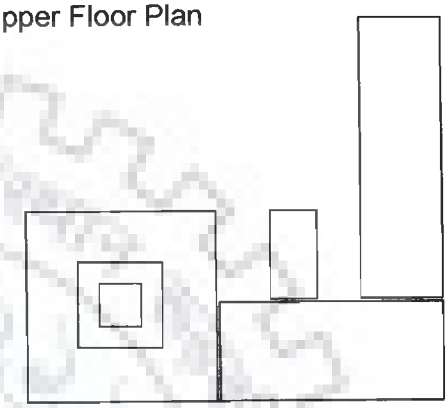
Main Floor Plan



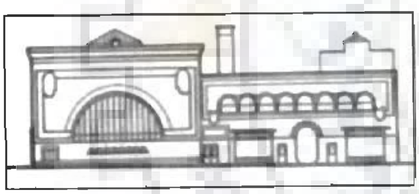
Upper Floor Plan



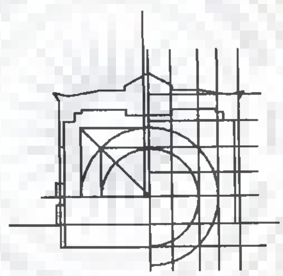
Plan Geometry



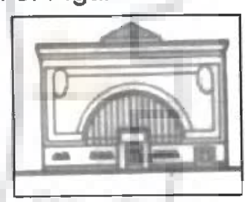
Disposition of Figures



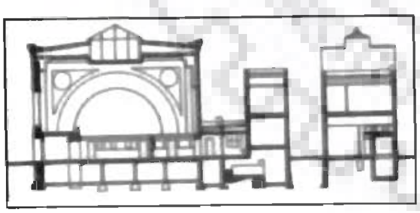
Right (South)Elevation



Front Elevation Geometry



Front(West)Elevation



Longitudinal Section

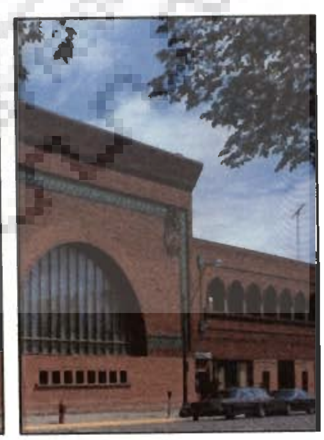
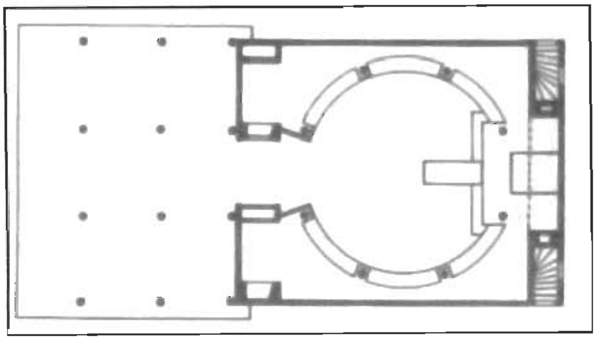
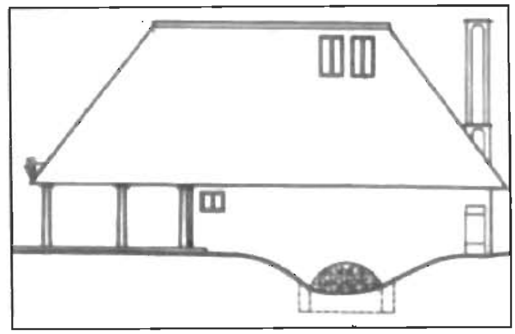


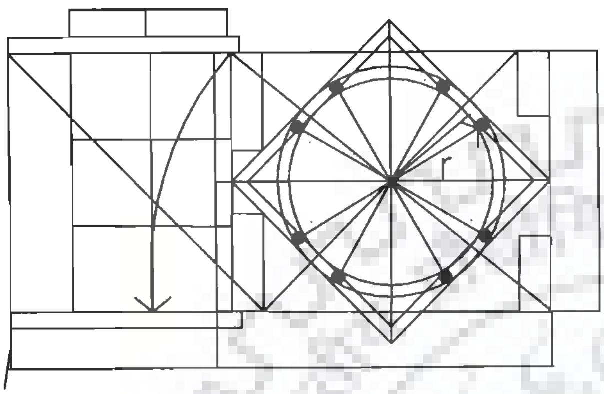
Fig 5.21 GEOMETRICAL ANALYSIS - NATIONAL FARMERS BANK MINNESOTA
Clark & Pause (1996)



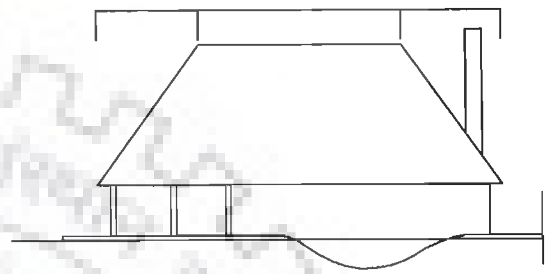
Plan



Section

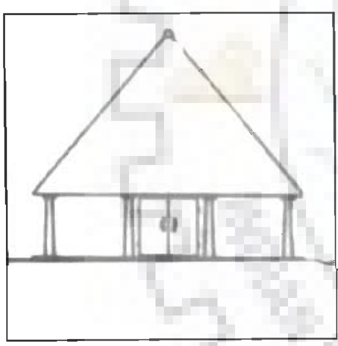


Plan Geometry

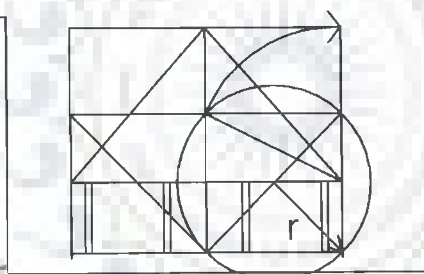


Right (south Elevation)

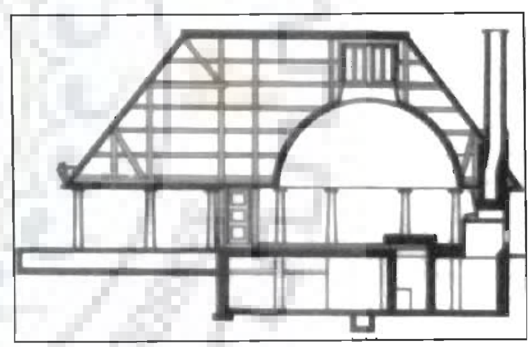
Elevation Geometry



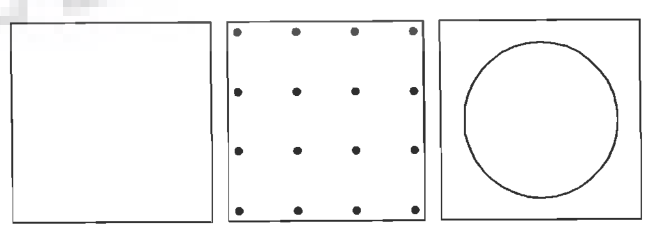
Elevation



Front Elevation Geometry



Longitudinal Section



Disposition of Figures

Fig 5.22 GEOMETRICAL ANALYSIS - WOODLAND CHAPEL
Clark & Pause (1996)

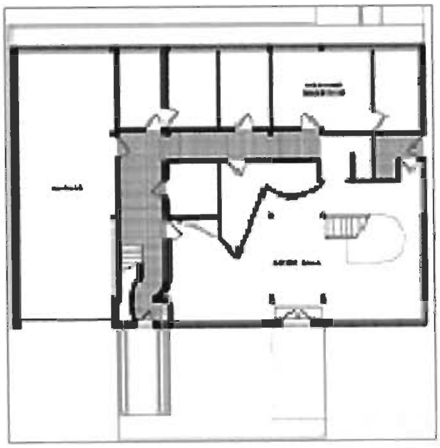
in nature with centralized spatial organization. The interior spaces are placed adjacent to each other and are linked by common space. There is frontal approach to building with linear movement pattern inside it. The path passes through spaces and terminates in a main space. The interior is built on human scale. The structure is a combination of compressive and tensile loading with load transfer through right angled and domical systems. Safety from earthquake is due to regularity, symmetry and lightness. Wood and brick are the structural materials used. Natural light enters directly through roof, indirectly and diffused through walls.

5.23. VILLA STEIN : GARCHES (1926 – 27 AD)

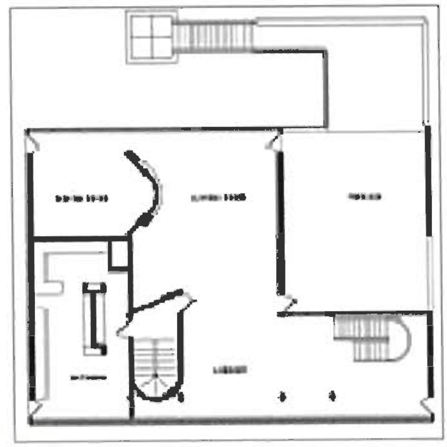
It is Le-Corbusier's most monumental and luxurious works of 1920s with main living spaces on the first floor and private suites on the second. The design, regulated according to the golden section, is asymmetrical. The structural grid is based in a rhythm of 2:1: 2:1:2 with respect to the end walls on one and 1.5:.5:1.5:1.5:1.5:.5 on the other side. The building has free plan with curved partitions. The factory glass at the lower level adds texture of the surface of the façade. It is considered to be the modern equivalent of Palladian villas. The rear facade has large glazed surface with terrace connecting this side to the garden.

The building thus contains musical and golden proportions along with use of regulating lines on the facades for aesthetic and functional reasons.

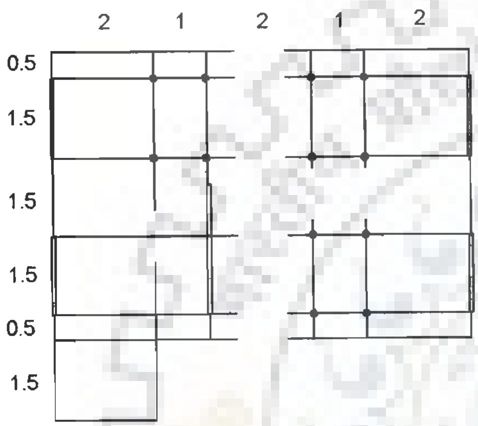
The form is regular with additive and subtractive character having centralized spatial organization. Because of free plan, the different spaces interlock with each other. The building is approached axially from front side.



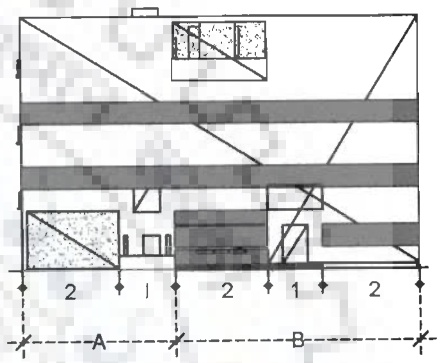
Ground Floor Plan



First Floor Plan

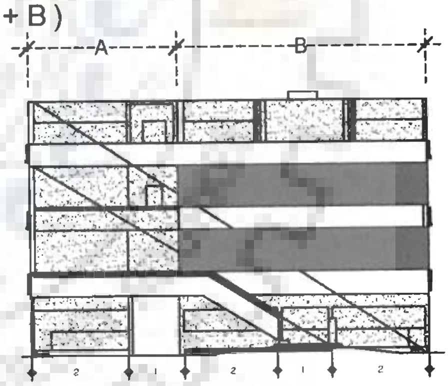


Structural Disposition According To Musical Proportions



Front Elevation Geometry

A : B = B : (A + B)



Rear Elevation Geometry

Fig 5.23 GEOMETRICAL ANALYSIS - VILLA STEIN
Rowe (1947)

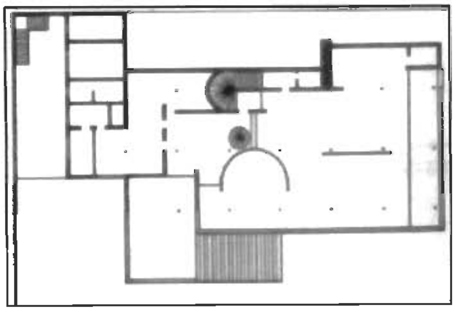
The movement does not possess any defined route and circulation is from one space to another.

The balcony, factory glazing articulate the surfaces giving it a visual weight. The structure is flexural with rigid right angled frame transferring the load to ground. From earthquake point of view, the building is regular and symmetrical, therefore safe. The structure has concrete pilotis, beams and slabs. Walls, non-load bearing, are of crude bricks. Natural light enters directly through them.

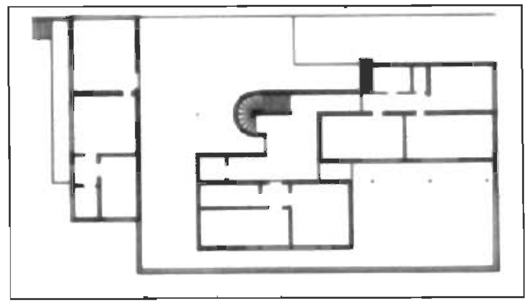
5.24. TUGHENDHAT HOUSE : BRNO (1929 – 30AD)

Designed by Mies Vander Rohe, it is on a hillside site which suggested two-storey building having the entry from rear side to the bedrooms above with main floor below. The building has open planning. Across the living and dining areas the entire wall is of glass whose two large panes slide down into pockets as the windows of automobile. A terrace and a flight of steps connect the house with the garden at lower level. The building is known for its thin chromium plated steel cross shaped columns held inside from the exterior walls which are kept glazed towards views.

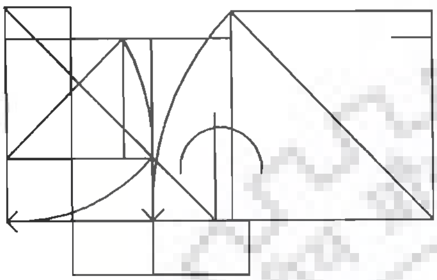
The simplicity of form and the juxtaposition of geometry with nature are very remarkable. The building construction on modern principles incorporated golden and geometrical proportions in its form. The form is additive and subtractive with clustered spatial organization. Different spaces are positioned within main space and at some junctures the spaces interlock with each other. The building is asymmetrical in its organization without any distinct hierarchy of parts. It is approached obliquely from outside with radial movement pattern inside. The structure has flexural loading with load transfers through non-rigid



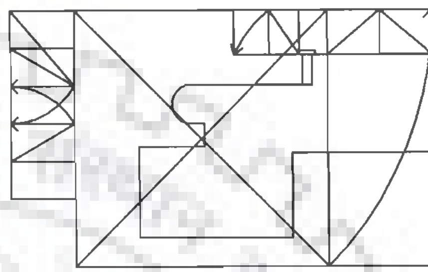
Lower Floor Plan



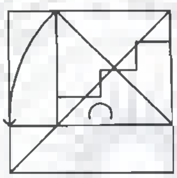
Upper Floor Plan



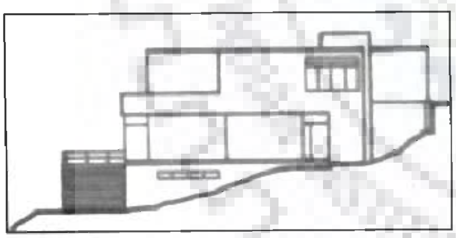
Lower Floor Plan Geometry



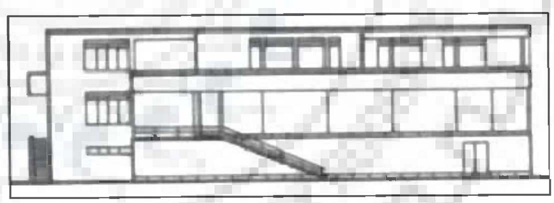
Upper Floor Plan Geometry



Part Plan Geometry



Side elevation



Front Elevation

Fig 5.24 GEOMETRICAL ANALYSIS - TUGENDHAT HOUSE

Clark & Pause (1996)

right angled system. The building's regular plan makes its safe from earthquake forces.

5.25. UNITE D' HABITATION : MARSEILLES (1947– 53 AD)

Designed by Le-Corbusier as a self-sufficient multifamily housing packed with all the necessary amenities with an open terrace at the top for leisure activities, it is a late-modern counter part of mass housing schemes of 1920s. It is a rectilinear reinforced grid into which precast housing units are slotted : Twenty-three different types of units, almost all with double-height living rooms, were designed to accommodate single persons as well as families with ten members. This twelve-storied apartment block was to house 1600 people. Housing slab, raised off ground on sculpted pilotis and sculptured façade with deep balconies are the salient external features.

The use of preferred dimensions in the form of modular, combining the dimensions form red and blue series, along with golden and geometrical proportions have been found to be incorporated for visual an functional reasons and human scale. The building pioneers the solution to housing problem in post world-war scenario. The form is predominately linear and regular articulated through addition and subtraction of different parts.

The spatial organization is also similar with different units placed adjacent to each other and linked by common linear movement space. Inside the units the spaces are interlocked with each other through the creation of double-heights and other methods. There is no visible hierarchy in this built form. The building is approached frontally as well as obliquely from outside with internal path passing by spaces. Visual weight is felt through giant massing and sculptured form with good co-operation among different scales.

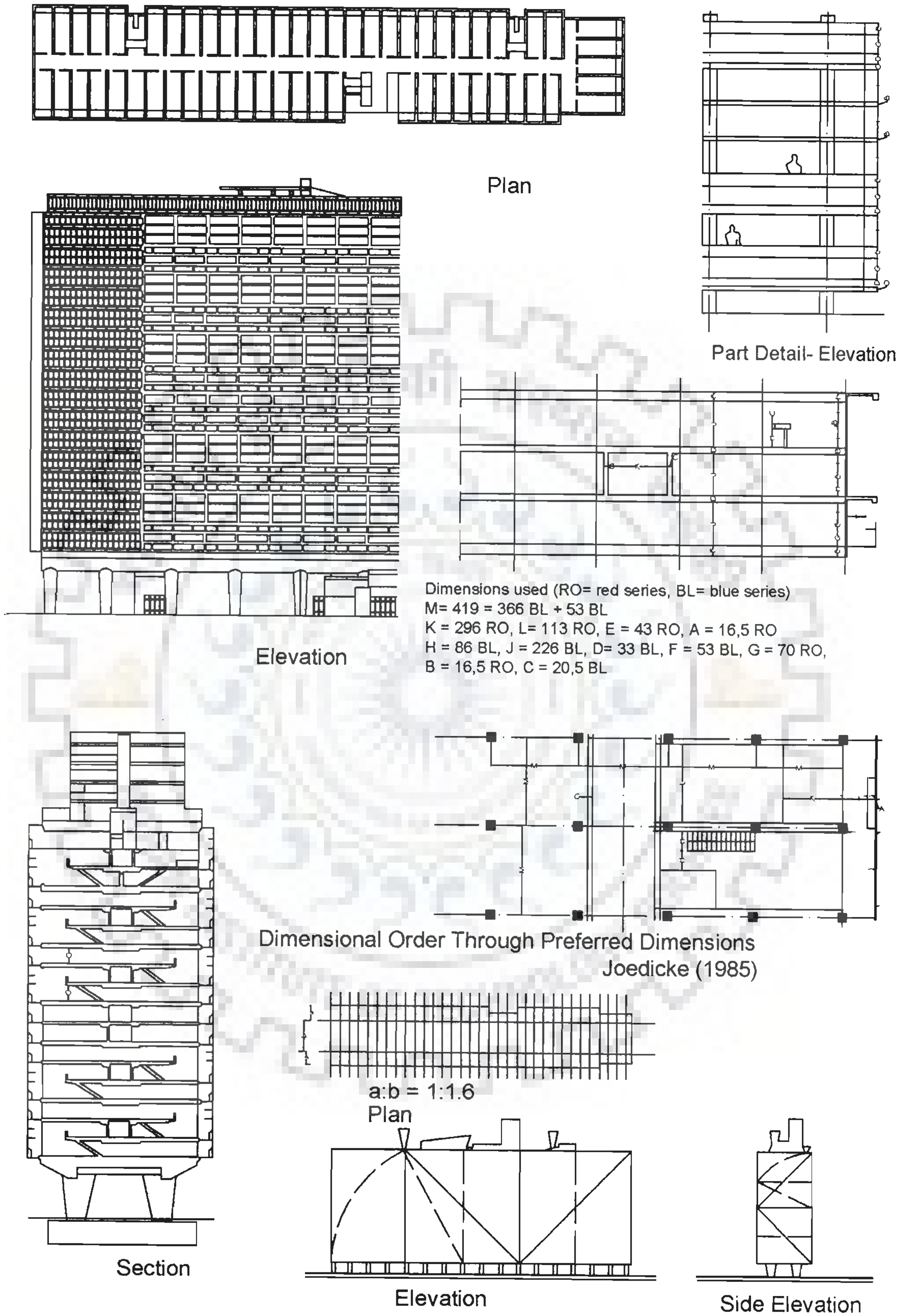
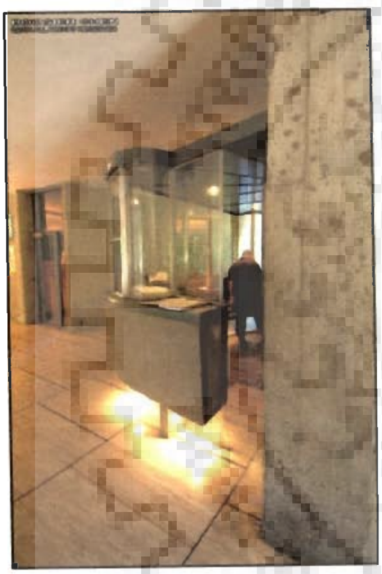


Fig 5.25 (a) GEOMETRICAL ANALYSIS - UNITE D' HABITATION

Unite D Habitation



Sarabhai House Interior

Terrace Unite D Habitation

Sarabhai House

Sarabhai House

Fig 5.25 (b) UNITE D' HABITATION AND SARABHAI HOUSE

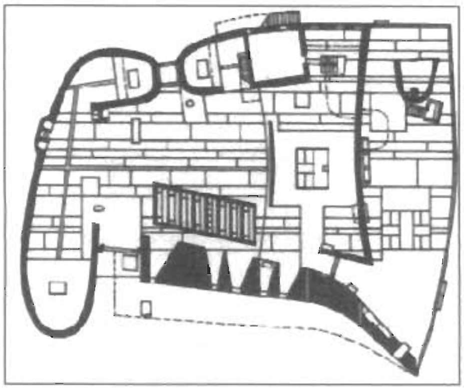
The structure is predominately flexural with small part at terrace having compressive loading because of shell roof. The load transfer is through rigid right angled RCC frame. Predominately, symmetry and regularity along with other measures, makes it safe from earthquake. Natural light enters the building directly through walls.

5.26. CHAPEL OF NOTRE DAME DE HAUT : RONCHAMP (1951– 55 AD)

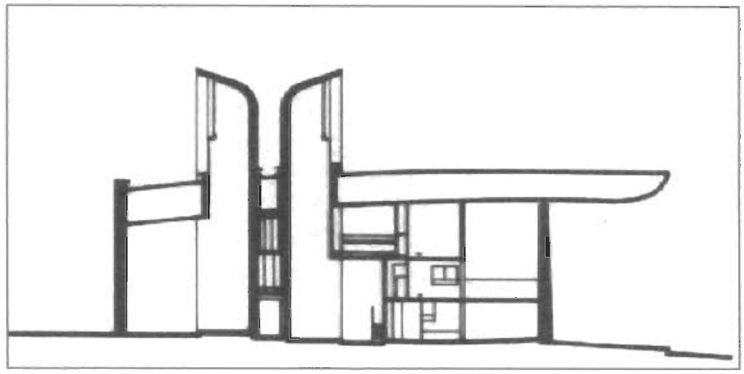
Designed by Le-Corbusier, the church is simple with oblong nave, an axial main alter, three chapels beneath the tower and two side entrances. This, one of the most matured works of late modernism, is a small building on a hillside in France is very expressive in its symbolic content which is enhanced by soft-form composition with deep windows of colored glass and the penetration of light from the thin linear gap between roof and walls. The structure is RCC frame with infill of rough masonry in walls which are faced with white washed Gunite (sprayed concrete) and roof is made of contrasting beton brut.

The systems applied here are geometrical proportions along with the use of modular with the dimensions taken from red and blue series and their combination, for spiritual and aesthetic purposes. It is a bold 20th century late modern composition with additive and subtractive volumes resulting in clustered form. The complex organization has spaces which are interlocked with each other.

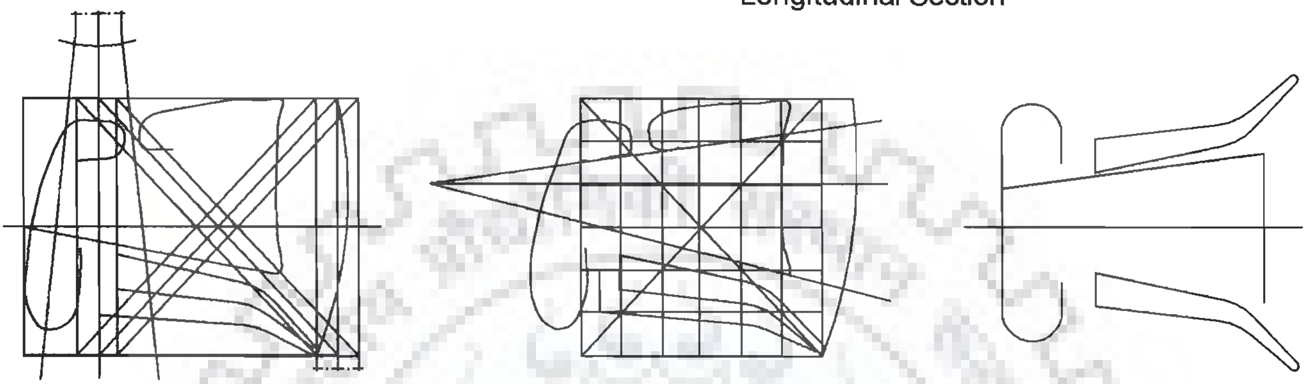
The plan is axial with highly asymmetrical composition. The building is approached obliquely from outside with linear configuration of movement inside it terminating in a space near main alter. Form is highly dominating



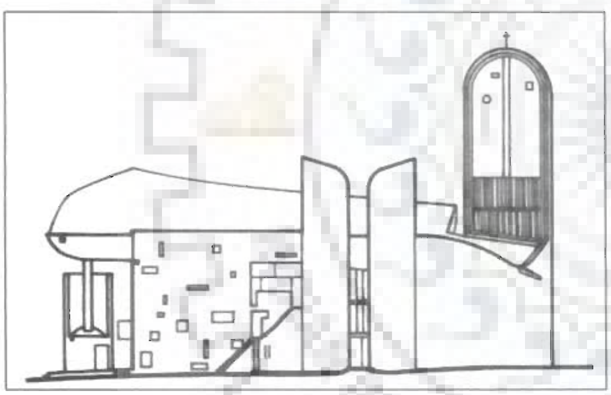
Plan



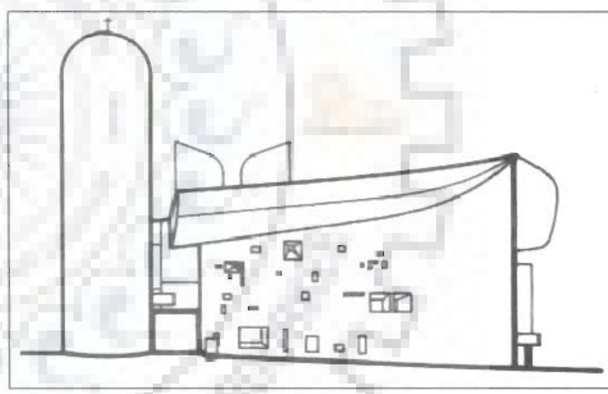
Longitudinal Section



Plan Geometry



Elevation



Elevation

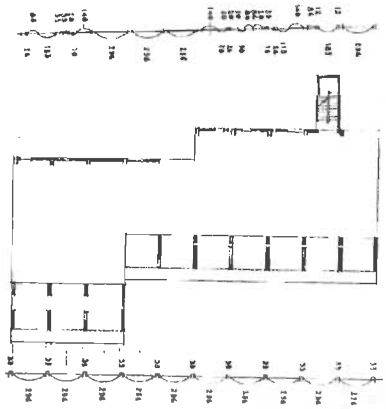
Fig 5.26 GEOMETRICAL ANALYSIS - CHAPEL OF NOTRE DAME DU HAUT:RONCHAMP
Clark & Pause (1996)

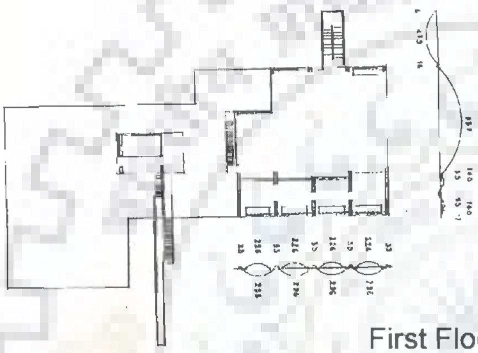
visually due to unconventional massing, and heavy surface articulation. Some elements are responding to visual order while other respect human scale with good co-operation among different scales. The structure is compressive with shell roof. Safety due to earthquake is assured due to controlled ratios between dimensions of length, breadth and height. Natural light enters in direct and diffused form from windows. Indirect diffused light just below the linear gap separating walls and roof articulates the interior.

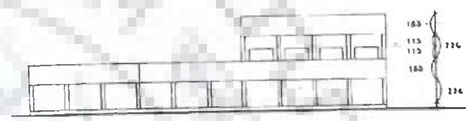
5.27. SARABHAI HOUSE : AHMEDABAD (1951– 55 AD)

Designed by Le-Corbusier for Mrs. Sarabhai and her two sons, he designed single storey block for the former and a double storey block with separate kitchen for the later while joining these two blocks by a carport. The exterior has concrete planes while the interior is organized through parallel brick walls with low concrete vaults resting on concrete beams. Services like toilets and bathrooms occupy the space between common walls and at times are free under the vault. By this way Corbusier here attained very clear space which acquired a sense of sheltered openness. The interior is therefore an open multipurpose space occupying most of the ground floor of the double-storied part of the house.

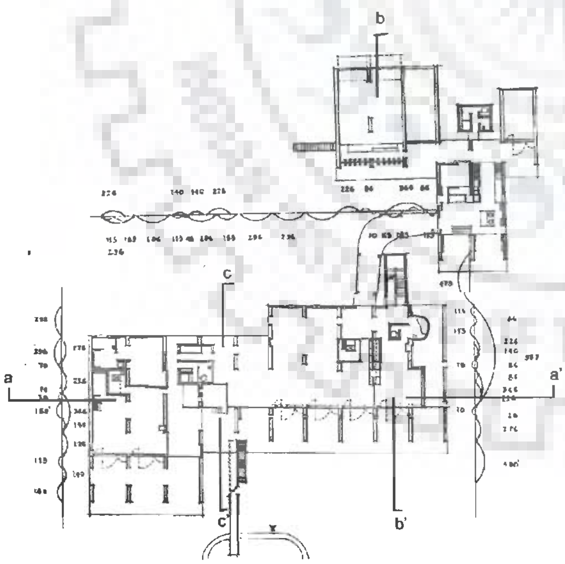
Preferred dimensions in the form of modular are applied for aesthetic and functional purposes along with the use of regulating lines to control the composition of the facades. The form is composed by adding different parts together making it a cluster in linear configuration with similar spatial organization. Interest is generated by interlocking different spaces with each other and placing others adjacent to them. The building is approached obliquely from out side with linear movement pattern inside. The arrangement

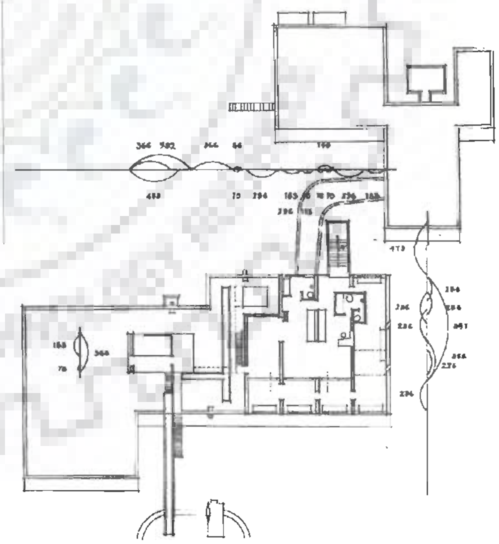






First Floor Plan



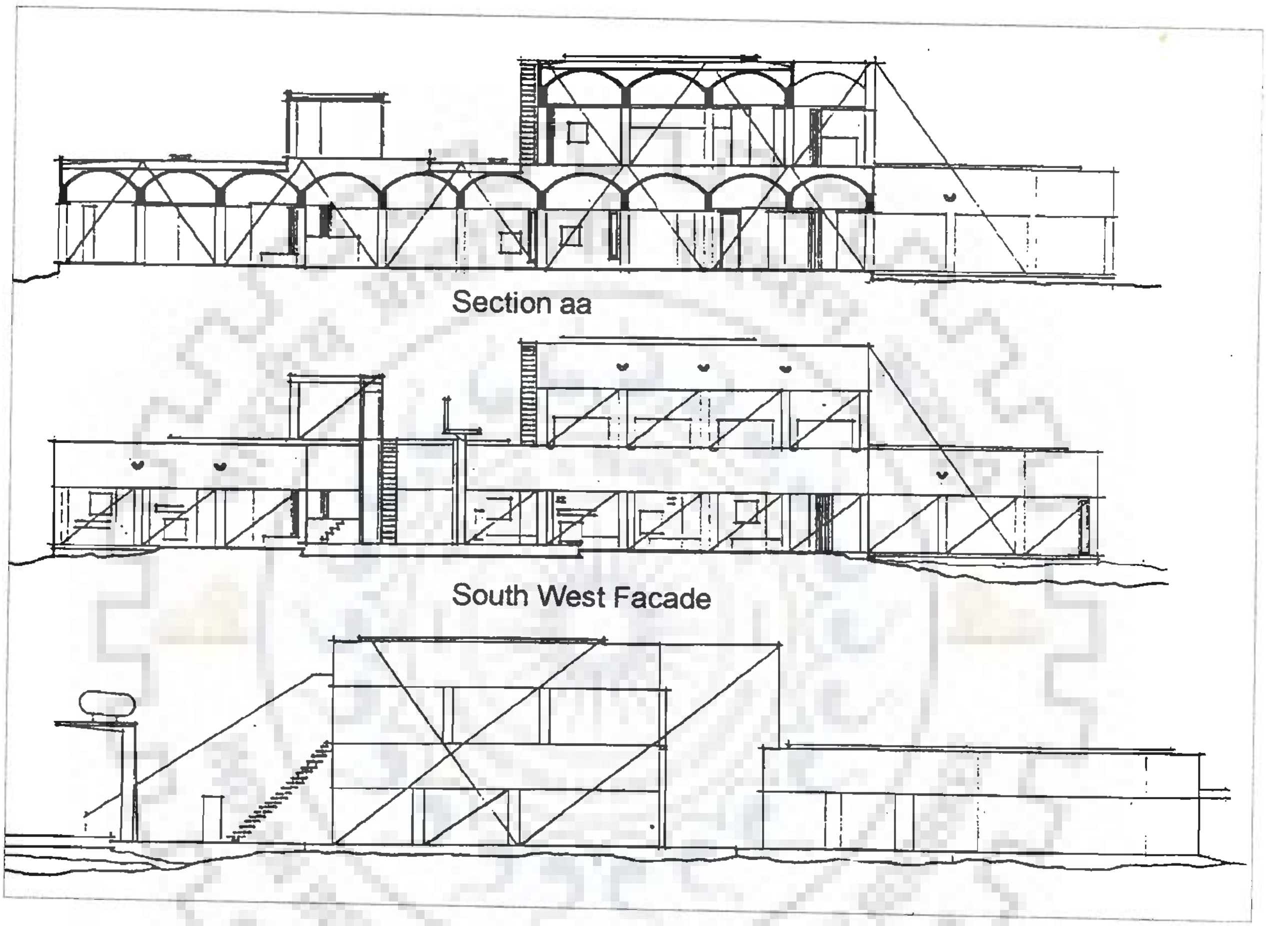


Ground Floor Plan

First Floor Plan

All Dimensions Are In cms

Fig 5.27 (a) GEOMETRICAL ANALYSIS - SARABHAI HOUSE
Dhabuwala (1996)



Section aa

South West Facade

South East Facade

Regulating Lines Controlling Section And Facades

Fig 5.27 (b) GEOMETRICAL ANALYSIS - SARABHAI HOUSE
Dhabuwala (1996)

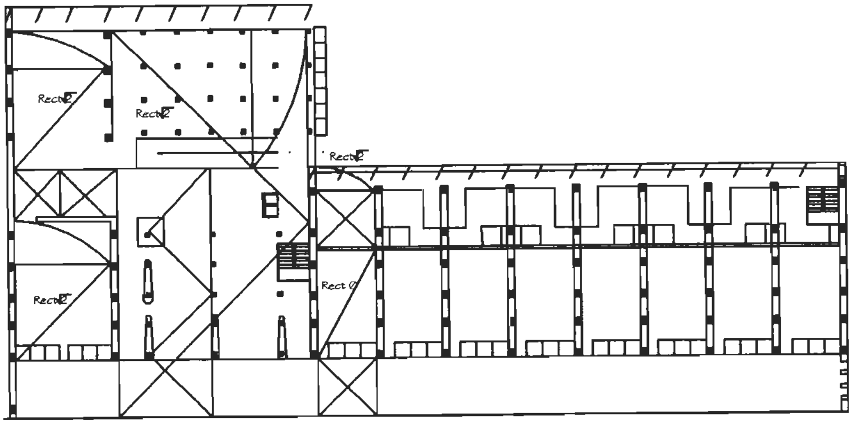
of parallel walls exhibits a sense of lateral and perpendicular movement creating a network system with movement route passing through spaces. The visual weight is through massing and surface articulation. The use of modular ensures human scale simultaneously generating good co-operation among different scales. The structure is compressive with non-rigid right angled load transfer system along with vaulting. Regular configuration of plan along with the controlled ratios among length, breadth and height, the structure is safe from earthquake. Brick and RCC are the structural materials used. Natural light enters in direct, indirect and diffused form through walls.

5.28. HIGH COURT : CHANDIGARH (1951– 55AD)

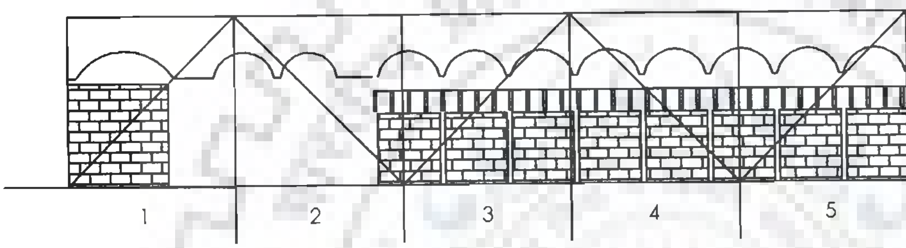
Designed by Le-Corbusier, High court and Parliament building of the Capitol Complex of Chandigarh, facing one another skipped, slightly off each other's axis and flanking Governor's Palace, expressed the idea of balance of powers between judiciary and executive. The High- Court, first building erected in the complex, is a huge open-sided box crowned by a giant roof standing on the 'grand order' of concrete piers. These piers, slightly curved in plan, define the asymmetrical entrance to the building, are painted red, yellow and green.

The main court organized along the left of entrance while others are arranged in a linear form to the right behind a system of sun-shading grills. Massive ramps link the different levels.

The organization has incorporated golden and geometrical proportions in it along with the use of modular to determine human and visual scale in its composition.



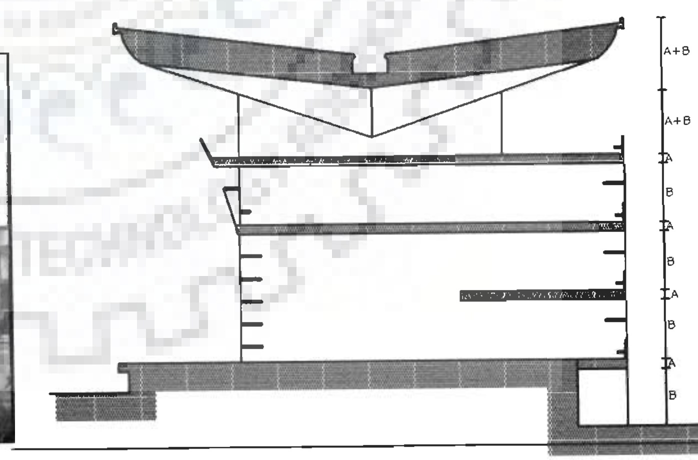
Plan Geometry



Elevation Geometry

Part Detail

Rear View



Section

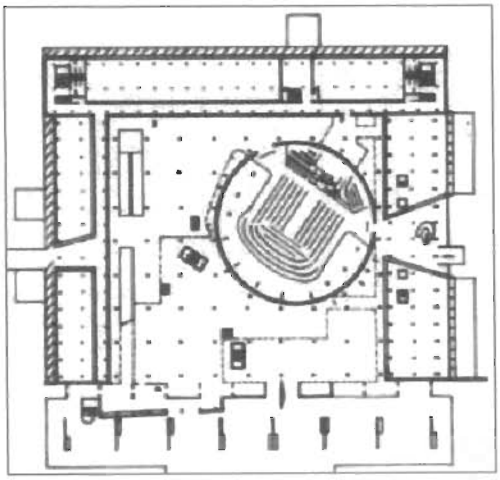
Fig 5.28 GEOMETRICAL ANALYSIS - HIGH COURT ; CHANDIGARH
Le - Corbusier (1955)

The form has been created by addition and subtraction of parts determining overall linearity with similar spatial organization. The form is determined by placing spaces adjacent to each other linked by common space and at some places this interlocking generate visual interest. The building is approached frontally with linear movement configuration inside it. The parasol roof adds to the visual weight which is further enhanced by the texture and interesting optical patterns generated by the use of brise-soleil screens on the two longer facades. The structure has compressive, tensile and flexural loading because of curved parasol and rigid right angled system with RCC as the structural material. Due to regularity and rigidity in form and controlled ratios among length, breadth and height, the building is safe from earthquake. Natural light enters directly and in diffused form through walls.

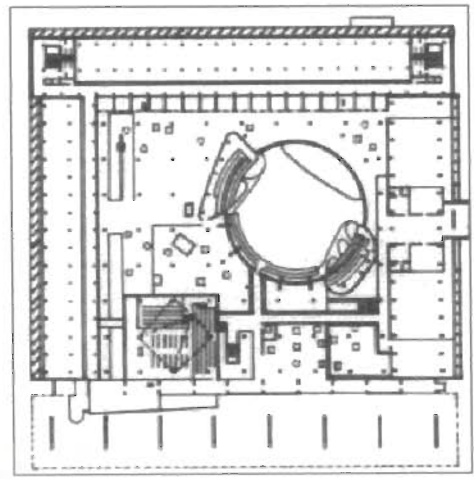
5.29. PARLIAMENT BUILDING : CHANDIGARH (1951– 63 AD)

Designed by Le-Corbusier, it is a large, introvert box with the front facing the plaza as a scooped portico, which looks like a gutter to drain water during rainy season. Constructed of RCC grid, it has free plan having main functional area defined by circular shape whose top is like a funnel with its tilted plaque, its upturned crescent and its downward turning curves. These roof volumes demarcate the main chambers and relate with mountains and the sky. The portico blends with these crescent themes. The routine entrance is to the secretariat side, two levels below plaza.

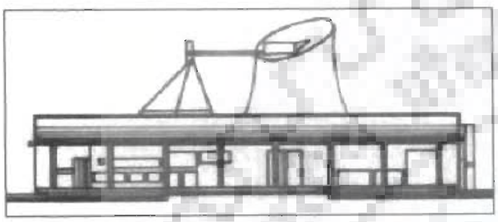
Golden and geometrical proportions along with the use of regulating lines to compose the organization and application of modular to relate different parts with each other and with the human being form the basis of this building. These systems were utilized for visual and functional reasons along



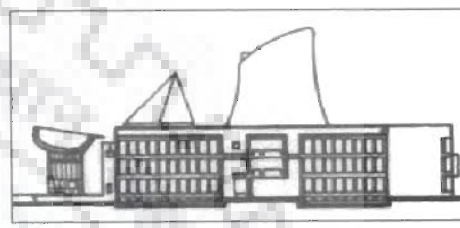
Lower Floor Plan



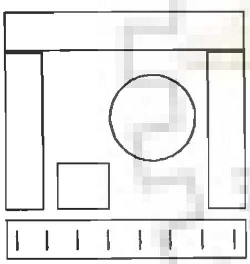
Upper Floor PLan



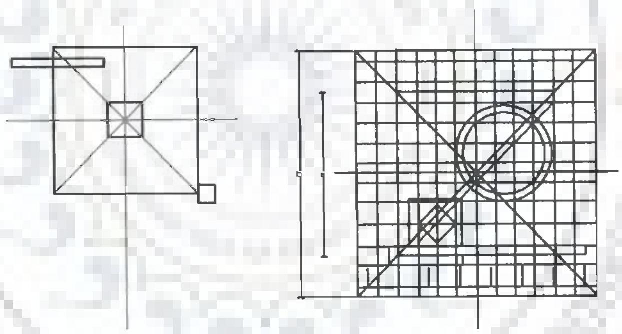
Front Elevation



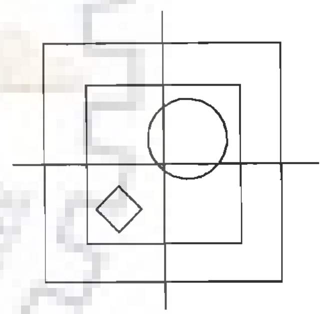
Right (North East) Elevation



Desposition of Figures



a : b = 1 : 1.6



Plan Geometry

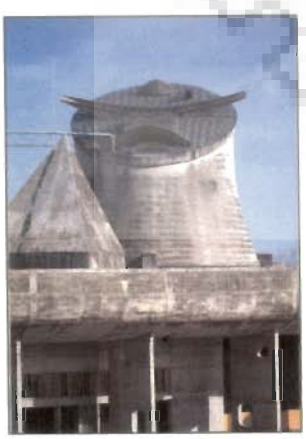


Fig 5.29 GEOMETRICAL ANALYSIS - PARLIAMENT BUILDING : CHANDIGARH
Clark & Pause (1996)

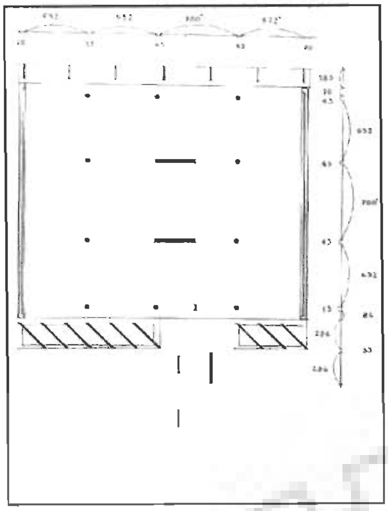
with attempt for generation the of 20th century equivalent of vernacular features. The form is regular with the parts added to describe a coherent whole. The spatial organization is predominately centralized formed by the cluster of different spaces put together. The dominating space is contained within overall cuboid. The interest is generated by the existence of main interlocking spaces, and secondary adjacent spaces linked by common space. The building is approached from two sides with composite movement pattern inside. The movement routes pass by spaces, go through spaces while terminating finally in the main space of assembly room. The building gains visual weight through contrasting interplay of masses, emphasized corners and surface articulation with the help of brise-soleil. The volume of assembly room is compressive with shell structure while the remaining building is flexural with rigid right angled frame of RCC.

Natural light through walls in direct, indirect and diffused form enters the interior while the assembly space is articulated by indirect light from roof.

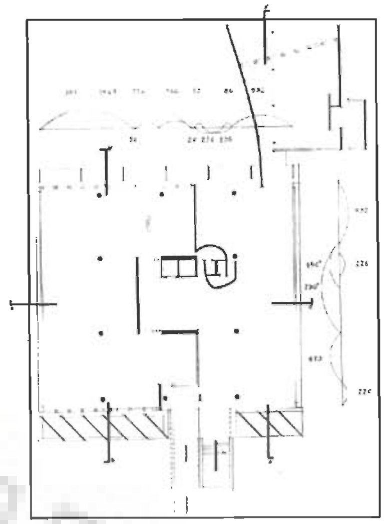
5.30. MILL- OWNER'S ASSOCIATION : AHMEDABAD (1954 – 56 AD)

The building was to reflect the power and eminence of the organization of Mill owners Ahmedabad. Le-Corbusier designed this building on a trapezoidal plot which flank river and road on shorter sides. Corbusier expressed institution's dual character – the private and the public through the concept of house as a palace which meant monumentality achieved through the use of pure forms organized according to harmonious law.

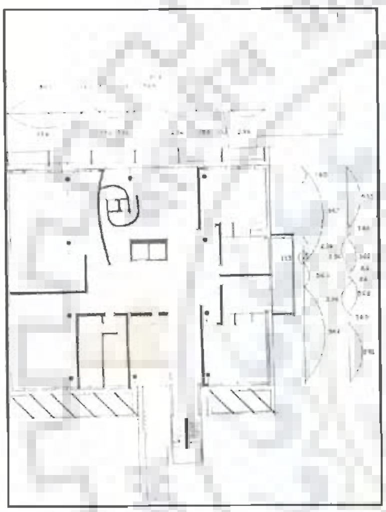
The entrance is approached frontally from the road to the building through ramp. On north and south the building is defined by two blank masonry panel walls. The central space is kept free on all the floors by



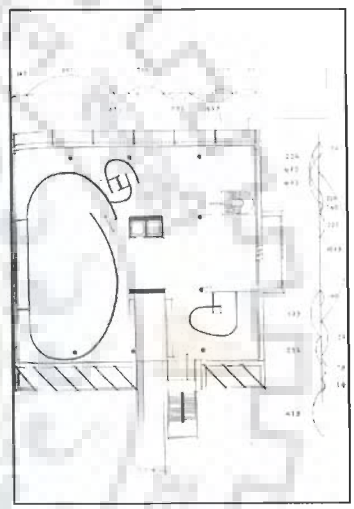
Plan



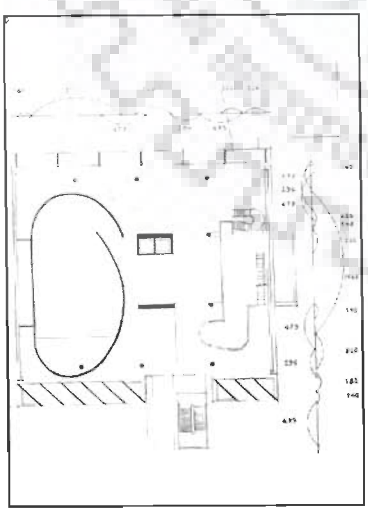
Ground Floor Plan



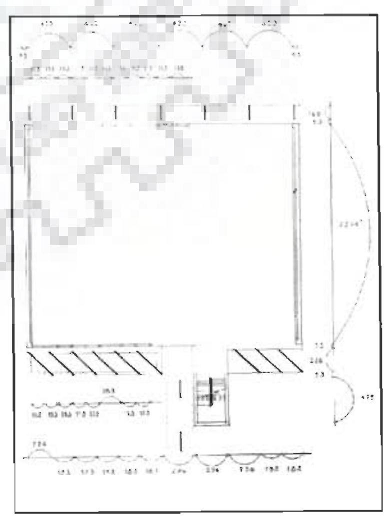
First Floor Plan



Second Floor Plan



Third Floor Plan

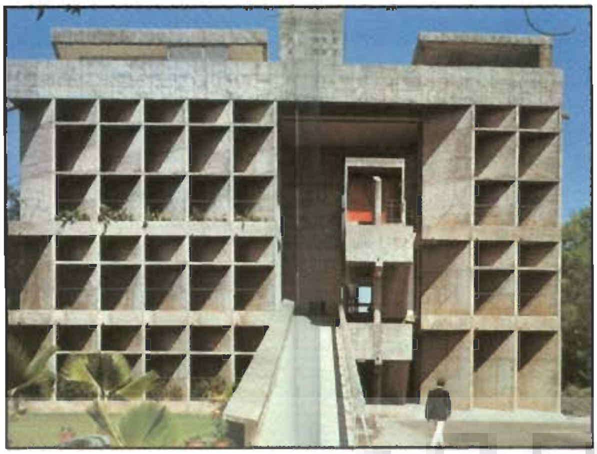


Dimensions of Parts

All dimensions are in cms.

Fig 5.30 (a) GEOMETRICAL ANALYSIS - MILL OWNER'S ASSOCIATION

Dhabuwala (1996)



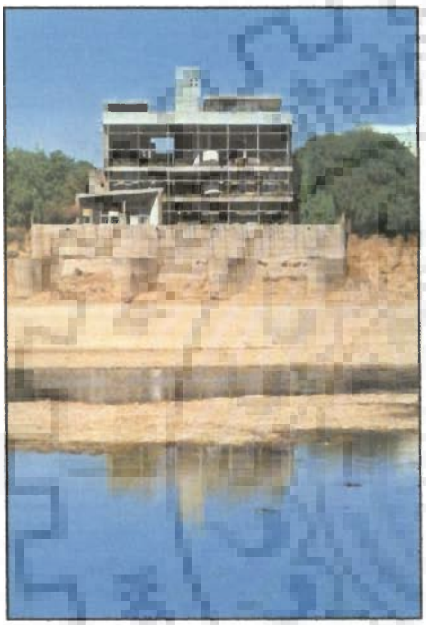
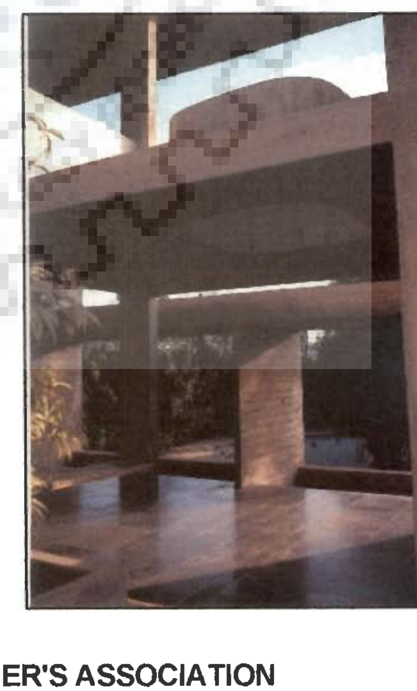
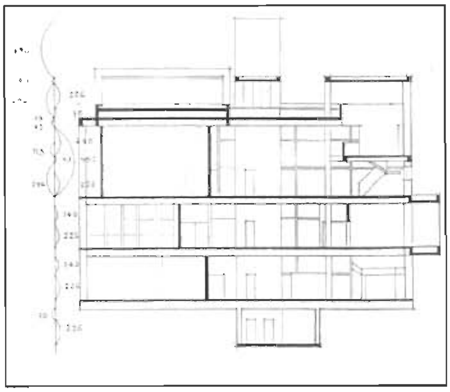
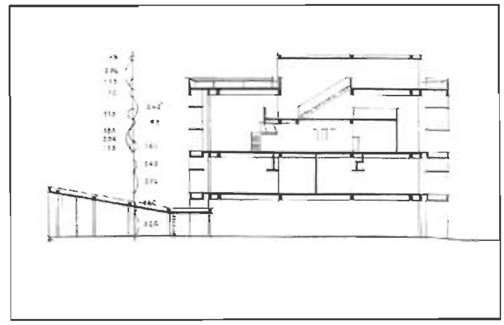



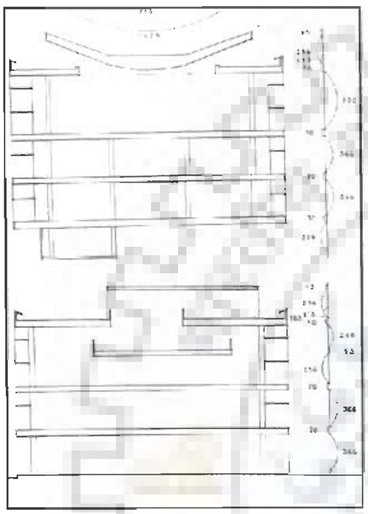

Fig 5.30 (b)   MILL OWNER'S ASSOCIATION



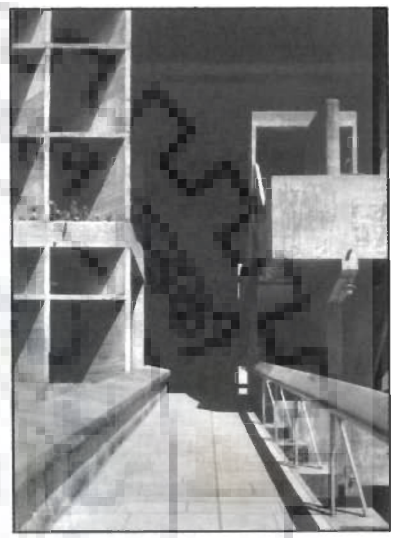
Section cc'

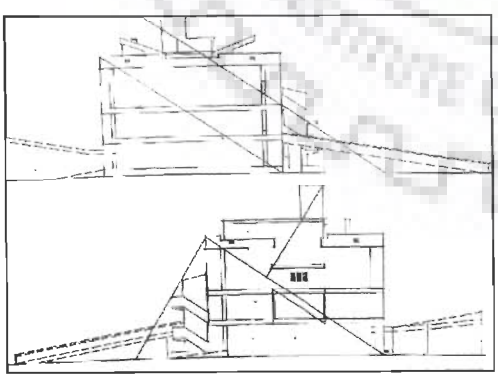


Section aa'

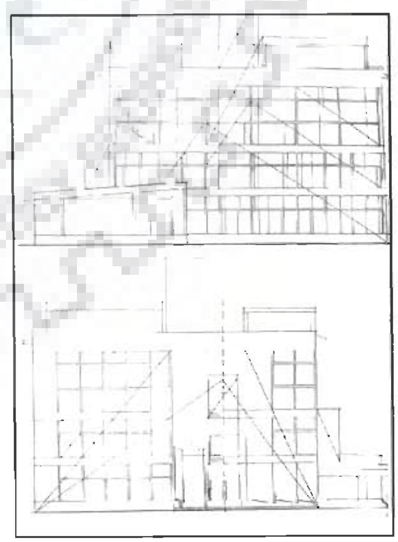


Section aa'





North Facade



East Facade

All dimensions are in cms.

Fig 5.30 (c) GEOMETRICAL ANALYSIS - MILL OWNER'S ASSOCIATION
Dhabuwala (1996)

attaching functions towards the sides. There are free locations of various elements such as toilet block, stair-cases etc. having curvilinear geometry creating dynamism between these forms and orthogonal grid. The building is cubical in form with square plan.

The use of golden and geometrical proportions is made along with regulating lines to control the composition of façade. Harmonic rhythm is achieved through the application of modular in determining the dimensions ranging from largest of the plan to the smallest in terms of thickness of sun-breakers as seen in figure. Use of geometry is made for visual and functional reasons and to make architecture suitable to its time. The form is regular and additive with clustered spatial organization. The main spaces are emphasized within overall cubical volume and interlocked with other spaces through the interplay of their varied heights. Common space in the centre links different functional spaces creating radial movement pattern inside. There is no visible symmetry and hierarchy in the form. Massing, sculptured façade created through the use of louvers and sun-breakers impart visual weight to the building. Use of modular ensures human scale in the composition with good co-operation among different scales. The structure is flexural with rigid right angled load transfer system. Because of rigidity, regularity and symmetry from earthquake considerations, the building is safe. Natural light articulates interiors by entering through walls directly, indirectly and also in diffused form. Indirect light penetrates through roof also.

5.31. VUOKSENNISKA CHURCH : IMATRA (1956 – 58 AD)

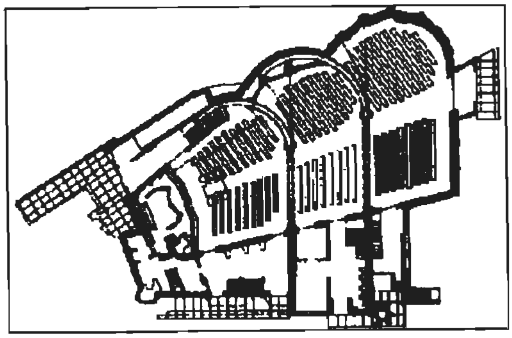
A completely asymmetrical building designed by Alvar Aalto, it is freely organized with the exterior having complicated form. The bell tower is like an arrow flying down to stick in the earth. It has three quill-like forms with three bells hung in between. The main auditorium is a shell form which can be divided into three parts to accommodate three different sizes of congregation. As per the requirement one third or two thirds of the church may be separated by sliding walls which are housed in the carved enclosures on the right hand side of nave. The curved ceiling is also designed innovatively in the form of three shells as dictated by acoustic requirements. When the partitions are in position the church can accommodate 290 people but when they are removed, 800 people can sit.

Golden proportions have been found to be incorporated in this design for spiritual and functional purposes. The overall form is a result of addition of parts forming clustered organization. The main spaces are interlocking with each other as can be seen in main hall while secondary spaces are placed adjacent to main space. The building is approached obliquely with linear movement pattern inside terminating in the main space.

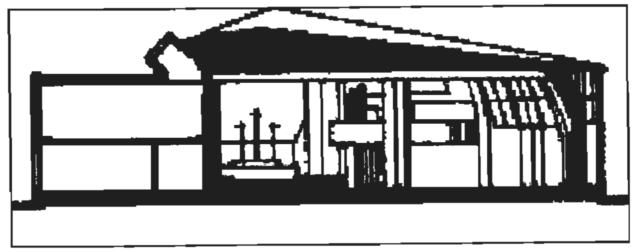
The visual weight is due to massing, color and optical patterns on the exterior. The building has mainly compressive loading with flexure at some places. RCC shell is the main structure. Brick is also used at some places as structural material. Natural light direct and in diffused form enters from walls.

5.32. SHODAN VILLA : AHMEDABAD (1951- 56 AD)

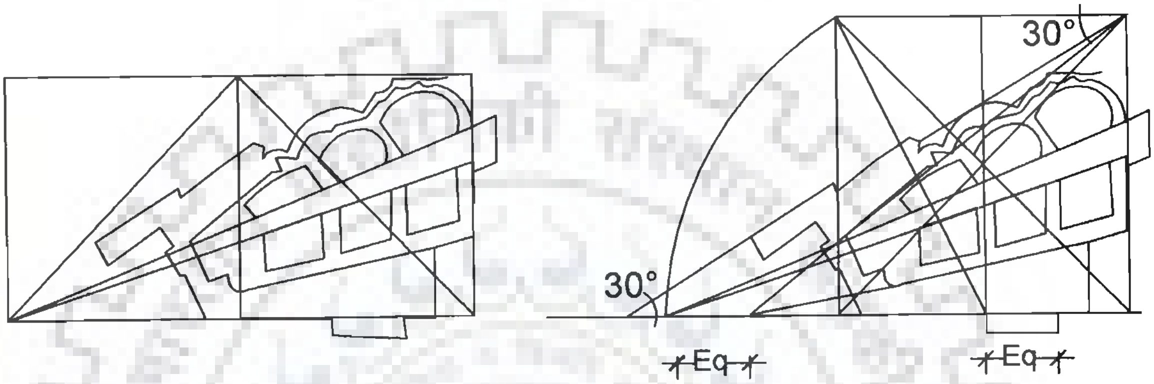
Designed by Le-Corbusier on its deep site, it is a cube in the surrounding landscape. It has a low-profile distinct entry, sharp and defined



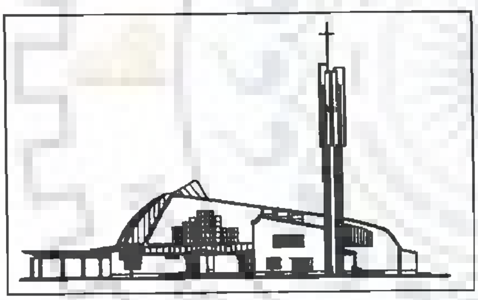
Plan



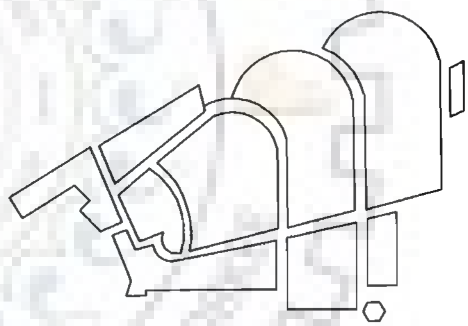
Longitudinal Section



Plan Geometries



Front Elevation



Disposition of Parts

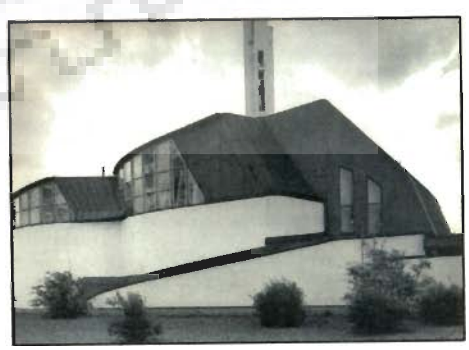
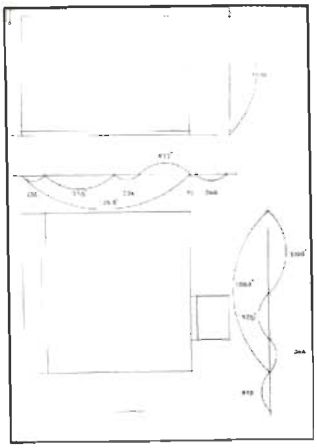
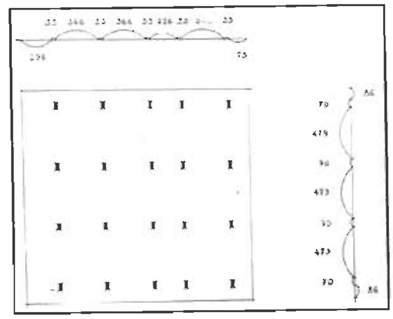


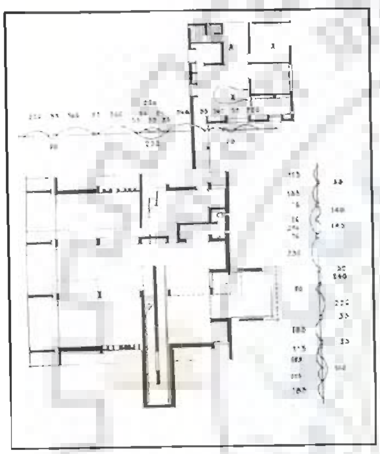
Fig 5.31 GEOMETRICAL ANALYSIS - VUOKSENNISKA CHURCH
Clark and Pause (1996)



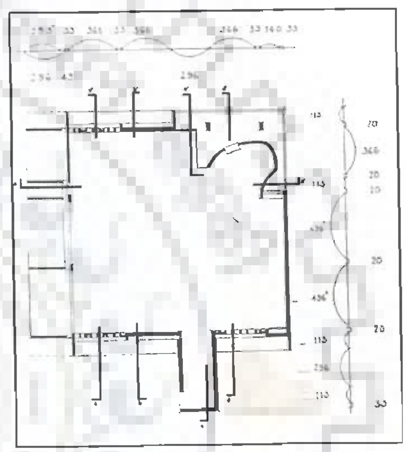
Plan



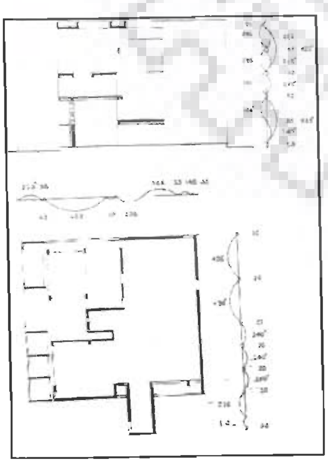
Structural Grid



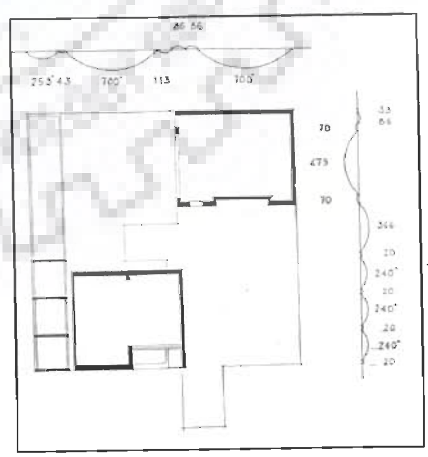
Ground Floor Plan



First Floor Plan



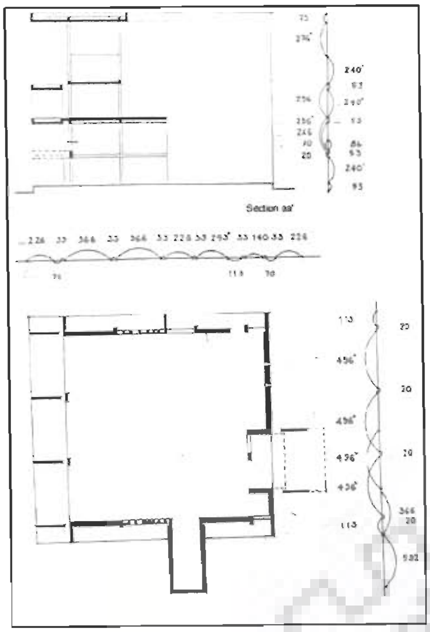
Second Floor Plan



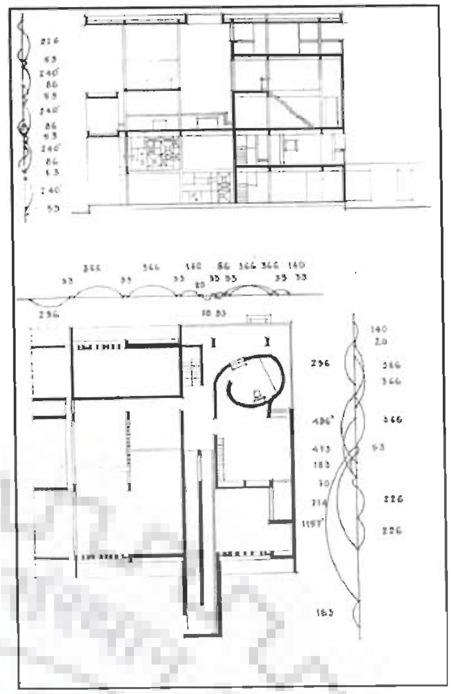
Third Floor Plan

All dimensions are in cms.

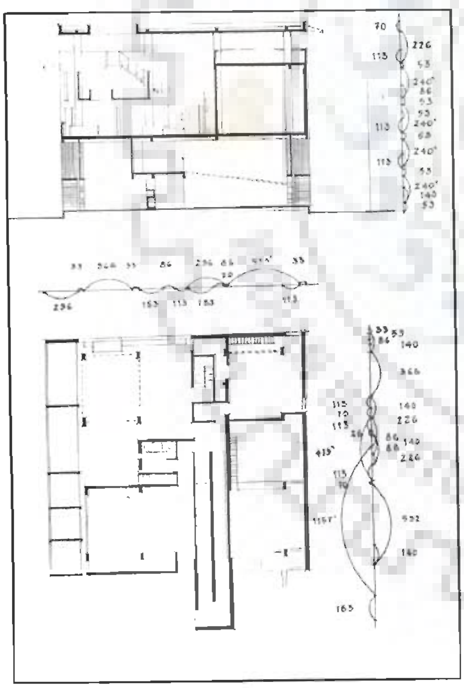
Fig 5.32 (a) GEOMETRICAL ANALYSIS - SHODAN VILLA
Dhabuwala (1996)



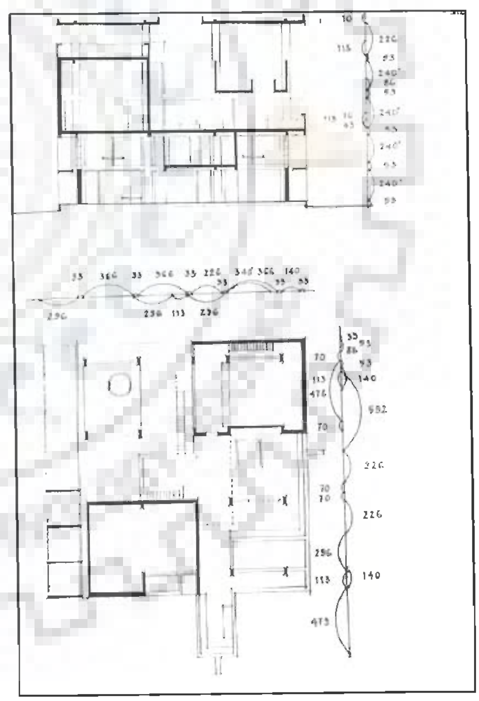
Ground floor Plan



First Floor Plan



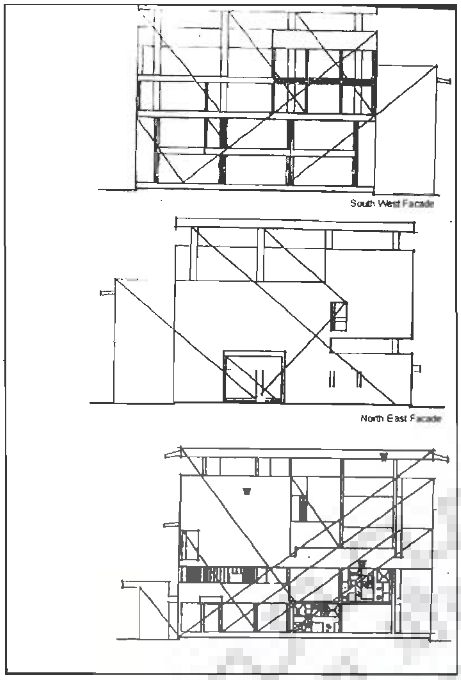
Second Floor Plan



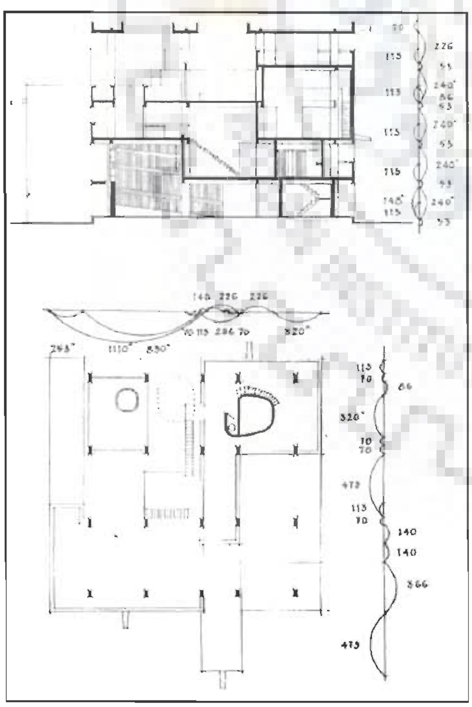
Third Floor Plan

All dimensions are in cms.

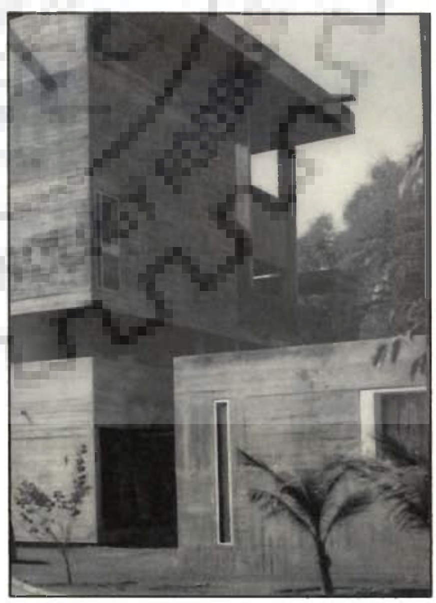
Fig 5.32 (b) GEOMETRICAL ANALYSIS - SHODAN VILLA
Dhabuwala (1996)



North West Facade



Fourth Floor Plan



All dimensions are in cms.

Fig 5.32 (c)   GEOMETRICAL ANALYSIS - SHODAN VILLA
Dhabuwala (1996)

mass with flat roof determined by continuous band of windows beneath it. The importance of design lies in its approach toward climate control and in its composition which is a result of interplay between lines and planes, horizontals and verticals, and between different colors. Services are located near the entrance and verandahs on the edge making the interior living space clear. The volume of the cube is divided by structural grid creating orderly and geometric variations from the combination of structural and non-structural parts.

Corbusier has applied his modular to attain harmonious rhythm in the dimensions ranging from the largest of the plan to the smallest thickness of the materials along with the use of regulating lines to control façade compositions as seen in figure. The building is late modern in which these geometrical systems are applied for visual and functional reasons. It is regular cube with some addition and subtraction of volumetric parts. The spaces are organized in clustered way. The small spaces are either properly enclosed by bigger ones or are interlocked with each other creating interesting interplay among them. The composition does not exhibit any kind of hierarchy and symmetry in it. The building is approached obliquely with orthogonal kind of movement inside the building. The spaces are approached by passing through other spaces as no well defined horizontal circulation is visible. The overall massing, the interplay of solids and voids on the outside, and light and shadow patterns add to the visual weight of the building.

By the use of modular, all the dimensions are related to human scale in parts within the entire or whole composition. The structural system is flexural with rigid RCC square gird dividing the volume of the cube in strict geometry.

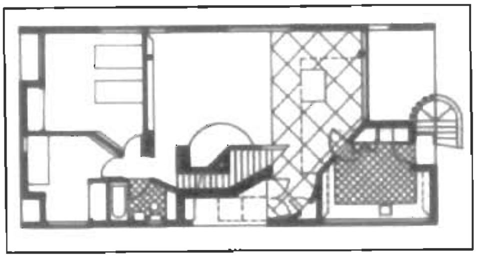
The building is safe from earthquake because of controlled ratios among different dimensions and rigid frame work. Natural light direct and indirect enters through walls. Roof also admits direct light to interior volume.

5.33. VANNA VENTURI HOUSE : PHILADELPHIA (1962 AD)

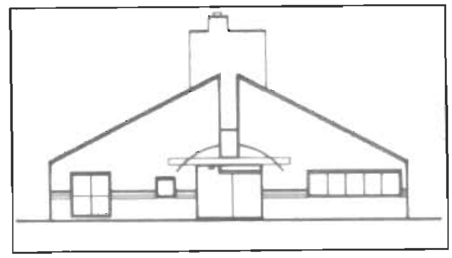
The house is based on symbolism interpreted in new way, twisted out of the normal context to be perceived differently. It has a rich reference to historic architecture. The façade and plan are almost symmetrical axial and monumental on the facing street but loose at the extremities and at rear. The house is centered on the idea of chimney, off centric in position, from which the spaces are pulled. The chimney rises up to split the house from outside. The façade is dominated by large gable, larger than it need to be with a split down in the middle acting as a visual device to emphasize large chimney element. The living room is half vaulted and this semi-circle is picked up in the tacked-on arch of the façade.

Golden proportions are applied to achieve functional efficiency and desired symbolism. The form is centralized and subtractive in nature with clustered spatial organization, having spaces simply placed adjacent to each other. The building is approached frontally with linear movement pattern inside passing through spaces. The design is based on human scale: Visual weight is perceived through massing and optical patterns on the exterior surfaces predominantly. The structure is compressive in loading with load transfer through non-rigid right angled system.

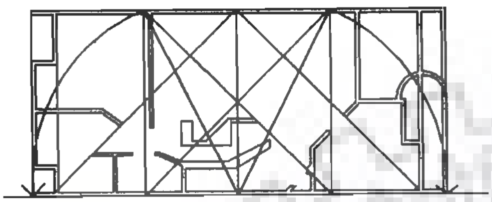
Because of overall regularity and symmetry the building is safe from earthquake. Steel girders are used in the roof with light wood and brick as other structural materials. Direct natural light enters through walls and roof.



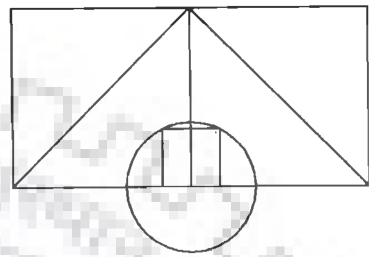
Plan



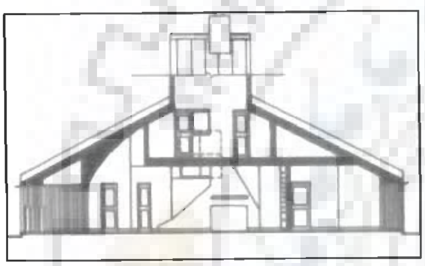
Elevation



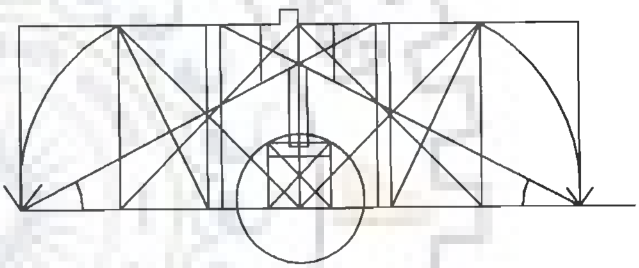
Plan Geometry



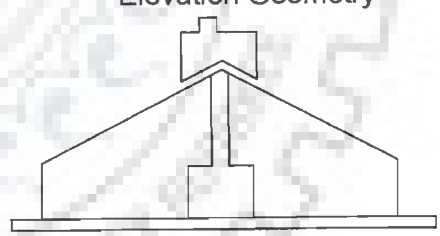
Basic Schema



Longitudinal Section



Elevation Geometry



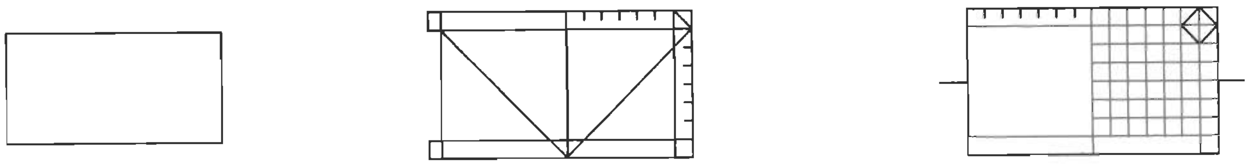
Disposition of Parts

Fig 5.33 GEOMETRICAL ANALYSIS - VANNA VENTURI HOUSE
Clark & Pause (1996)

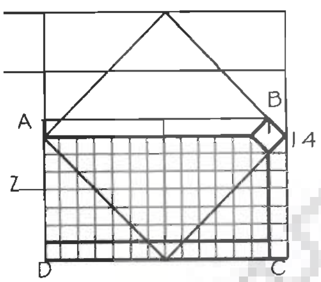
5.34. SCHOOL BUILDING – INDIAN INSTITUTE OF MANAGEMENT : AHMEDABAD (1962– 74 AD)

Designed by Louis I. Khan, IIM has three clusters around water body one for school, other for dormitories and the third for faculty housing. The school consists of library, offices and classrooms on a U-shaped plan with orientation towards the direction of prevailing winds. The light wells, courts and loggias minimize the penetration of sun. It is one of the most matured works of Kahn with his preoccupation with light and silence giving form and order to his building. The openings on the walls of corridor around the central courtyard are few and such they give it a sense of monumentality. The building has rigor of geometry, well- defined masses and monochromatic built form. The apertures of the buildings, their directions and surfaces of the load-bearing brick walls confining the openings add to the monumental character of the institution. It is further enhanced by main entrance with the ground steps in oblique direction placed axially to the existing mango tree.

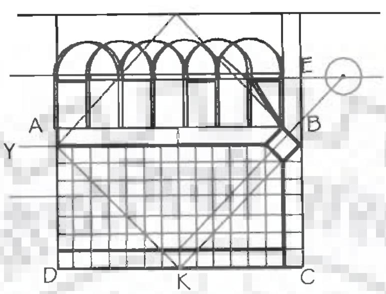
The building is based on golden and geometrical proportions with strict geometrical modules of different volumes placed around u-shaped courtyard. The application of geometry is found to have been applied for aesthetic and monumental reasons. Different units are added to give it an overall regular form dominated by centralized court with linear movement corridor around it. The interplay of volumes through large apertures and varied heights interlock different spaces with each other. The building is axial, symmetrical around main court with no clear hierarchy in form. The movement routes pass through main common spaces while simply going by secondary ones. The massing of the building, texture and color of thick exposed brick walls with



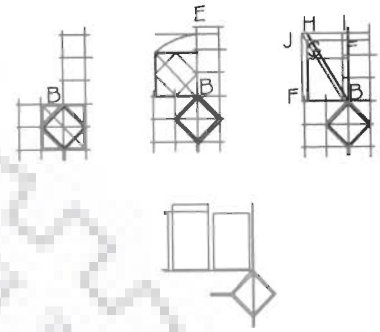
Begining of IIM With Double Square of CourtYard



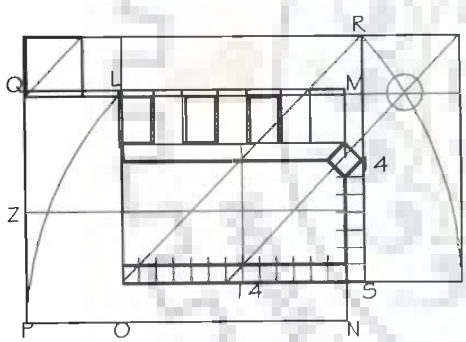
Courtyard Figure And
Mirror Axis With
Entrance Square



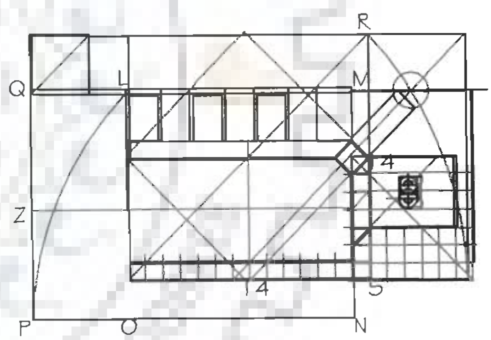
Development of
Administration Figure



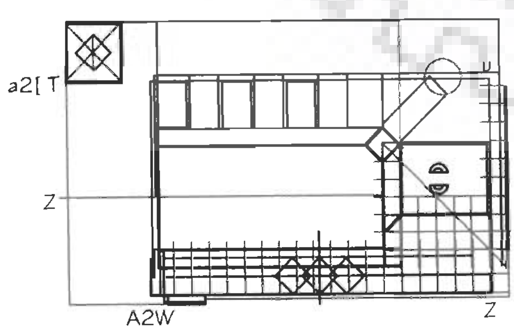
Development of Administration
Figure From The Geometry
of Entrance Square



Dependance of Subsequent
Figures on The Centre

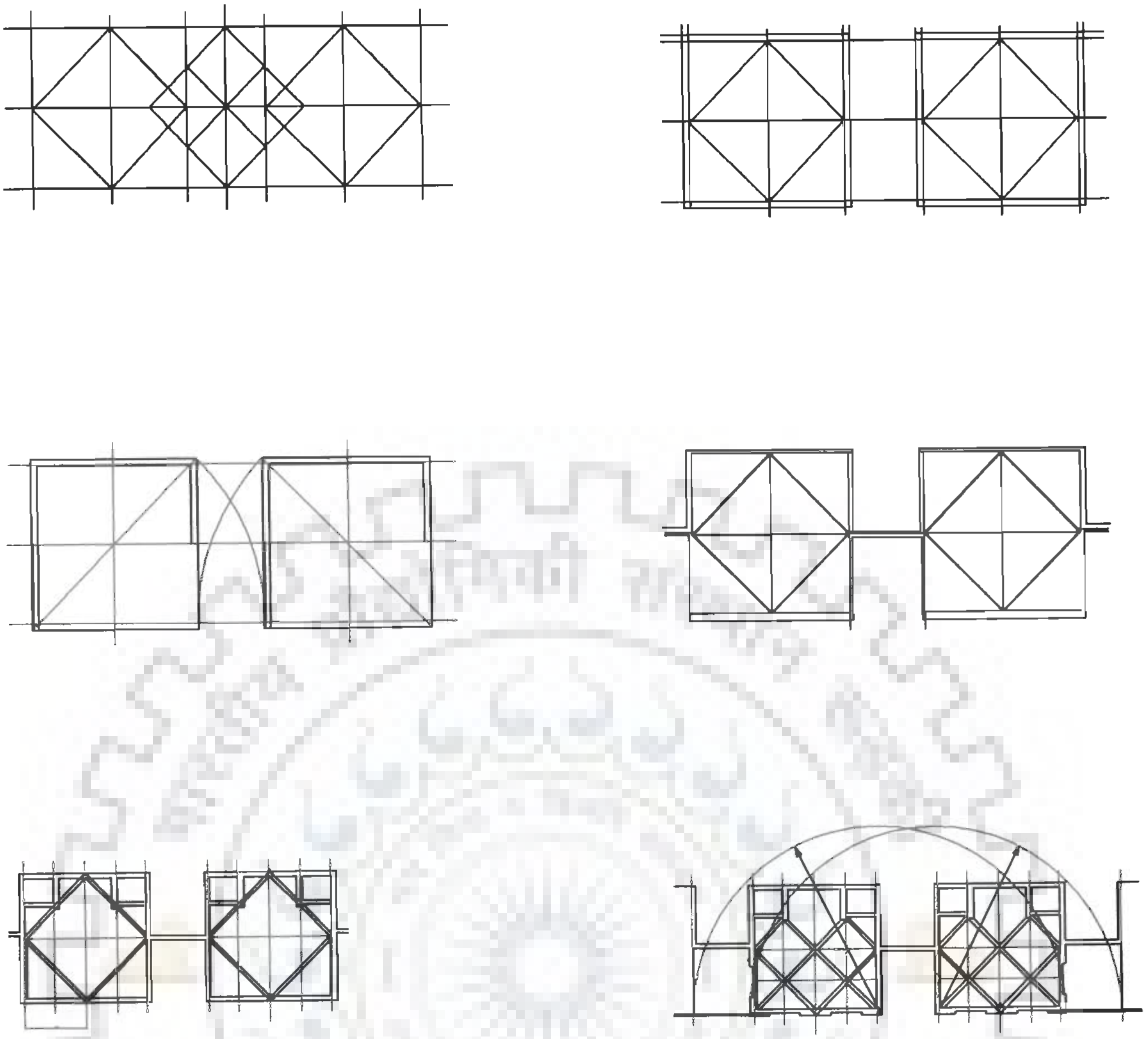


Devlopment of Library Figure
And The Main Entrance

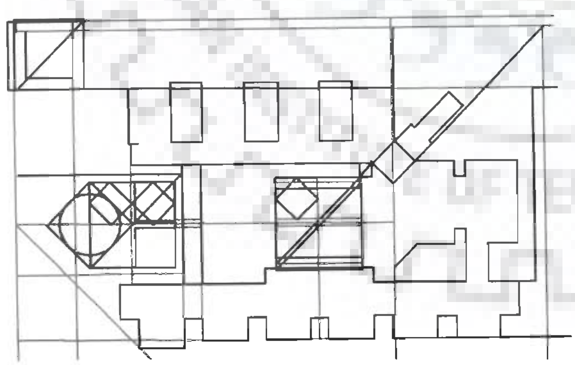


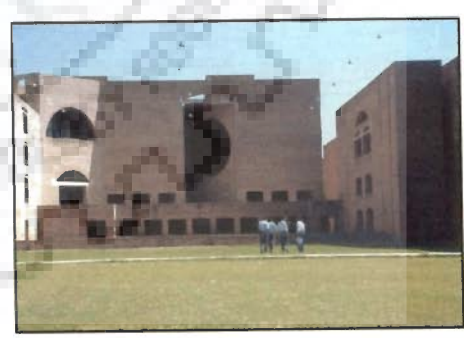
Development of Classroom Figure
And The MainEntrance

Fig 5.34 (a) GEOMETRICAL ANALYSIS - INDIAN INSTITUTE OF MANAGEMENT AHMEDABAD
Gast (1998)



Devlopment of Classroom Figure





Devlopment of Dining - Kitchen And The Amphitheatre in Relationto Entrance Square

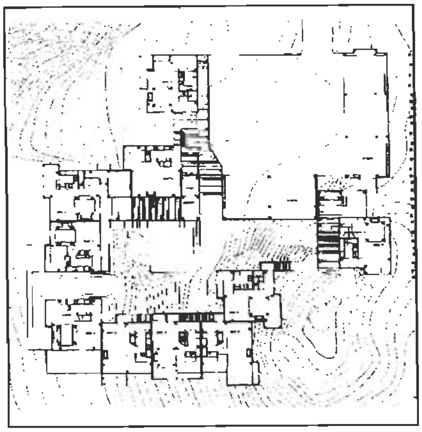
Fig 5.34 (b) GEOMETRICAL ANALYSIS - INDIAN INSTITUTE OF MANAGEMENT AHMEDABAD
Gast (1998)

giant apertures impart strong visual weight to the form. The structure is flexural with non-rigid right angled load transfer system. Regularity, symmetry and controlled ratios among different dimensions make it safe from earthquake. Brick and RCC are the main structural materials. Natural light in direct and indirect form articulates the interior spaces.

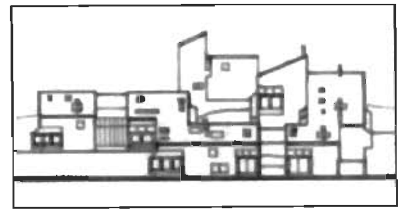
5.35. SEA-RANCH CONDOMINIUM I : CALIFORNIA (1966 AD)

These multifamily housing units of wood and timber frame designed by Moore Lyndon Turnball Whitaker are grouped around central courtyard with traditional shed roofed massing giving the flavor of local vernacular. The clustered organization was created to preserve the openness of rugged and beauty of site.

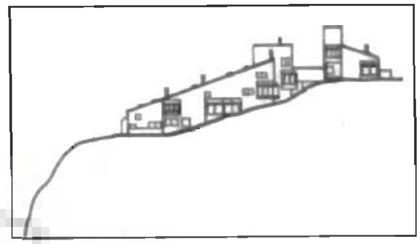
Use of module based approach in the form of individual units and geometrical proportions has been made for aesthetic and functional reasons. The form is additive and clustered with spaces organized adjacent to each other without any distinguished hierarchy of parts. The approach to this housing is spiral in shape with linear movement pattern inside. The paths pass by spaces thereby linking them with each other. Visual weight is perceived due to massing, surface texture and color. The housing is designed on human scale with good co-operation among different parts. The structure is compressive with non-rigid right angled load transmission. Being light weight it is safe from earthquake. Direct natural light is achieved through wall surfaces,



Plan

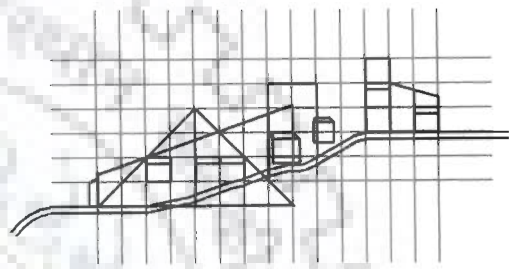


Sea SideElevation

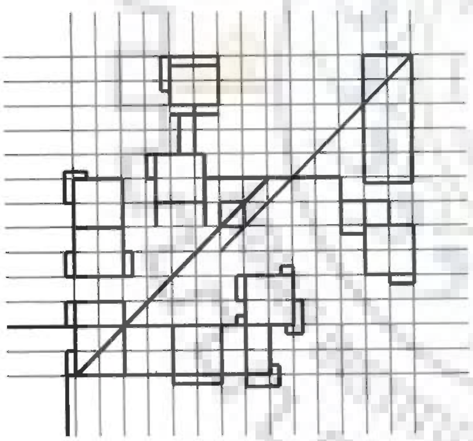


Rear Elevation

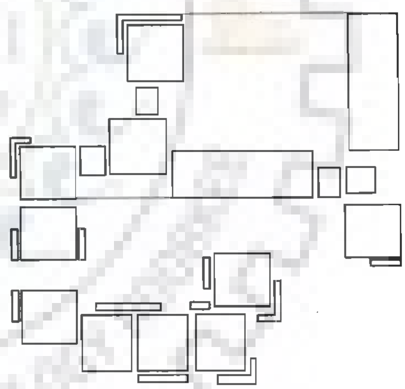
Basic Schema



Elevation Geometry



Plan Geometry



Desposition of figures

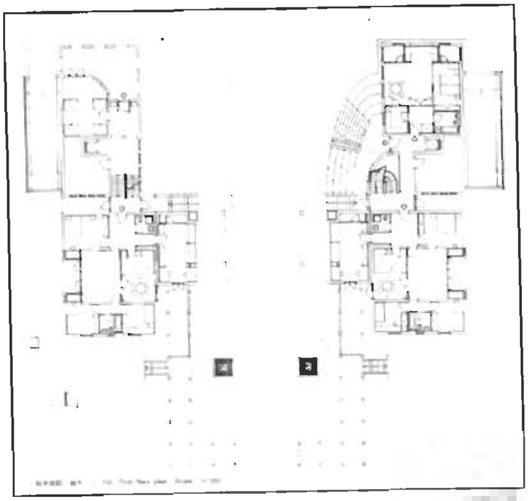
Fig 5.35 GEOMETRICAL ANALYSIS - SEA RANCH CONDOMINIUM I
Clark & Pause (1996)

5.36. RITTERSTRASSE HOUSING : BERLIN (1977– 80AD)

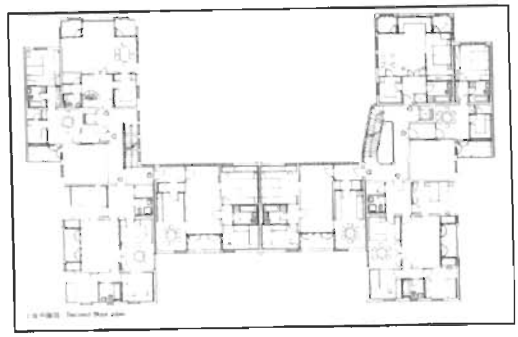
Designed by Rob Krier, the form of the building is determined by the urban context from the beginning. The building displays center of the section facing Ritterstrasse in the north end district. The path leading to the entrance and extending towards the centre of the township is emphasized. The form of stair-cases has been given special attention carved like pieces of sculpture. The arches connecting two parts in front and back are purely ornamental without any structural importance. The pillars between windows become wider as they move to the top. The houses get all the sunlight through the windows and the terrace. Vibrant colors have been applied to the outer surfaces of the building.

The architect applied golden and geometrical proportions along with regulating lines to determine the geometry of the facades and their parts as shown by him in the figure for purely aesthetic purpose. The housing units are added to result in a clustered form. The spatial organization inside each house in both the sections across the road is radial. The spaces are interlocked with each other at some junctions while simply grouped adjacent to each other at other places. The form is symmetrical with no visible hierarchy among part. The building is approached obliquely with linear movement pattern inside. The movement goes through different spaces. Visual weight is perceived because of rich optical patterns on the facades apart from the use of vibrant color. Parts of various scales have good co-operation with each other.

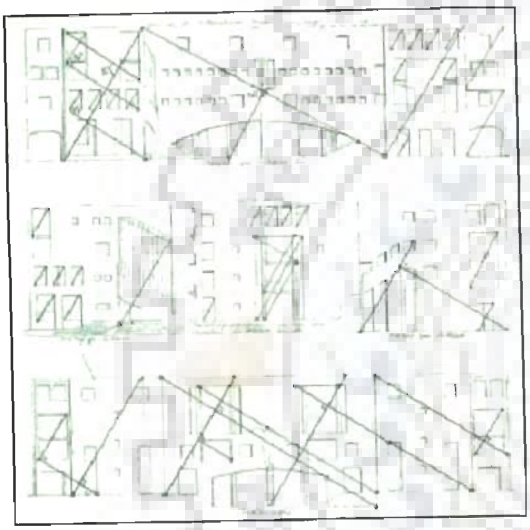
The structure has flexural loading with load transfers through non-rigid right angled system with brick and reinforced concrete as main structural



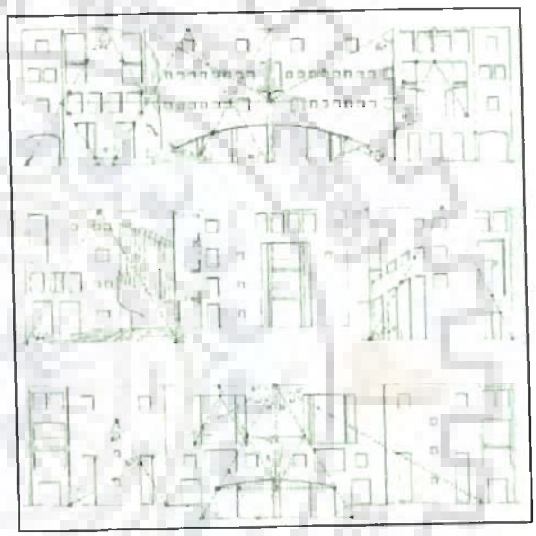
Ground Floor Plan



First Floor Plan



Proportion of The Facade ,
Width To Height = 1 : √3



Proportion of The Facade ,
Width To Height = 1 : √3/2

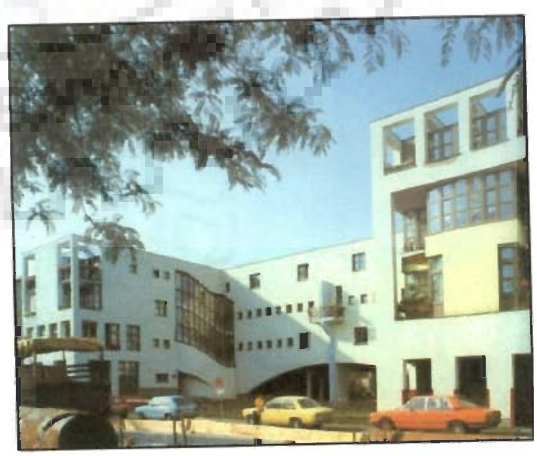


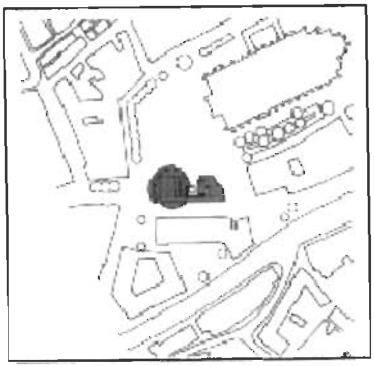
Fig 5. 36 GEOMETRICAL ANALYSIS - RITTERSTRASSE HOUSING
Krier (1981)

materials. Because of regularity and symmetry in plan and elevation, the building is safe from earth quake.

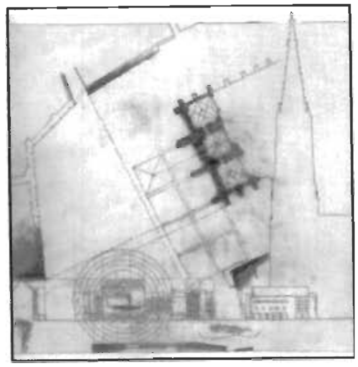
5.37. ULM EXHIBITION AND ASSEMBLY BUILDING : ULM (1986– 90 AD)

This building is designed by Richard Meier in the historic context in the form of Ulm cathedral of 14th century. Meier through his design enhanced vistas of the cathedral while maintaining the open space in front of it by placing his building - a curved structure made up of light berge stone with white plaster on one side of the square. He organized the open space with paving whose module was derived from the cathedral. This exhibition and assembly building houses city's tourist office, exhibition space and assembly halls along with other spaces. The building takes visitor to the observation deck on the roof for views of cathedral and then back to the ground.

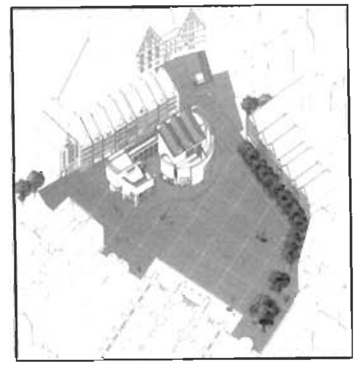
Meier has incorporated module-based proportions with the size of the module taken from cathedral along with the use of regulating lines for aesthetic reasons and to respect the context while maintaining its 20th century architectural character. The form results from the subtraction of few parts from pure solid form. It has clustered spatial organization with main spaces interlocking with each other while secondary spaces are linked by common circulation areas. The building does not exhibition any axial organization. It is approached obliquely from outside with linear movement pattern inside. The movement path passes through main spaces while going by secondary ones. The visual weight is gained through textured surfaces and optical patterns in outer walls and in the form of gabled roof-tops. The building shows good co-operation among parts of different sizes. The structure has flexural loading using rigid right angled frame. The building is asymmetrical in nature but



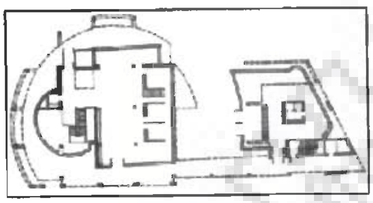
Site Plan



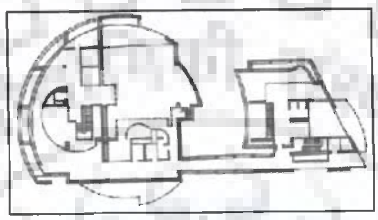
Concept



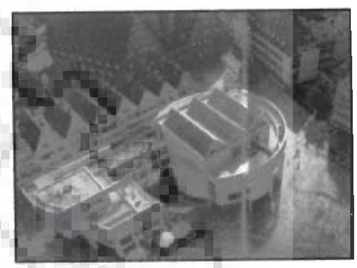
Axonometric

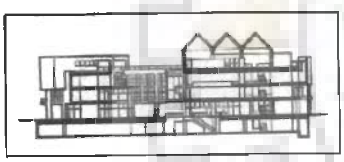


First Floor Plan

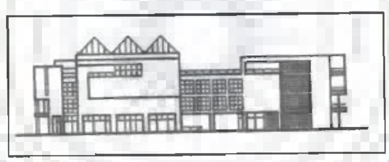


Second Floor Plan

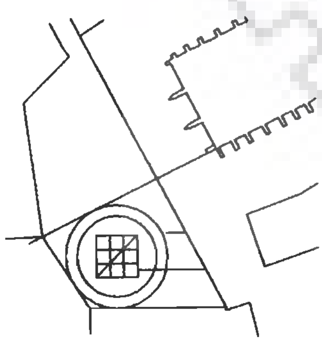




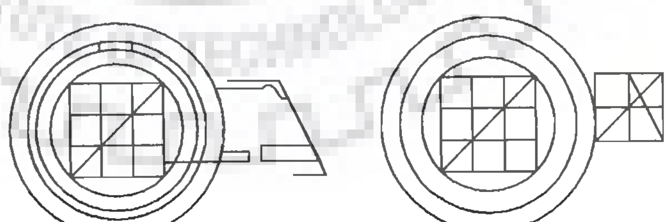
Longitudinal Section



Side Elevation



Conceptual Geometry



Plan Geometry

Fig 5.37 GEOMETRICAL ANALYSIS - ULM EXHIBITION AND ASSEMBLY BUILDING
Clark & Pause (1996)

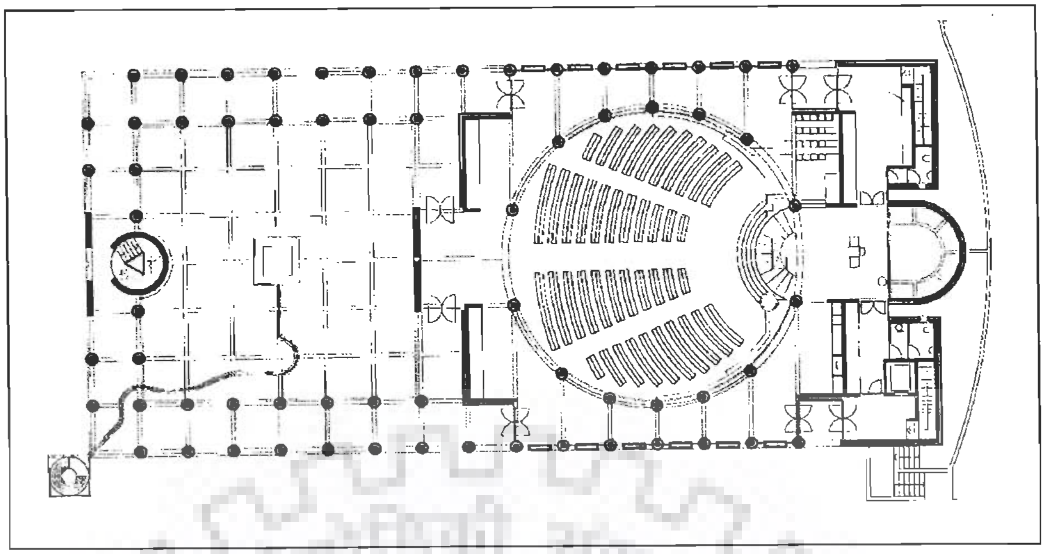
exhibit safety from earthquake through the controlled ratios between length, breadth and height. Along with stone, reinforced concrete is also a major structural material used. Natural light enters through walls in direct and indirect form; while roof surfaces allow only direct penetration of it.

5.38. CHURCH OF BEATO ODORICO : PORDENONE (1987– 92 AD)

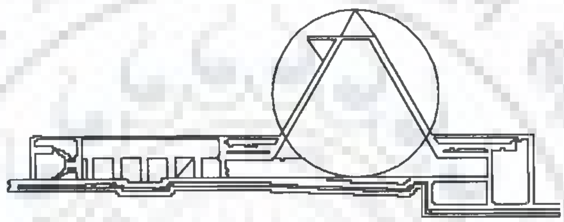
Designed by Mario Botta, the church has a simple plan with dominating conical primary volume, rising above the surrounding buildings. The design acquires a different direction by fresh interpretation of a need that seems to flare higher in contemporary man. The large rectangular section of courtyard, defined by colonnades on four sides, lead man to the space meant for attaining higher goals. This space is crowned by rusticated brick facing cone with slanting opening at the top emphasizing cone's hollowness. At the tip of the cone, two metal brackets cantilever the bell out from the cone. The interior space finally terminates in semi-circular apse. Regular rhythm of column spacing also continues inside the church clearly demarcating main space. Bright light filters down through the cone articulating the otherwise somber & monumental interior.

The form is based on the clear juxtaposition of geometrical figures of square and circle. The spatial dimensions are based on the module-based proportions. These geometrical systems are applied to achieve spirituality, aesthetics and functional efficacy specifically for contemporary man. The form is newly interpreted to suit 21st century church. It is simultaneously regular, additive, subtractive and linear in its composition.

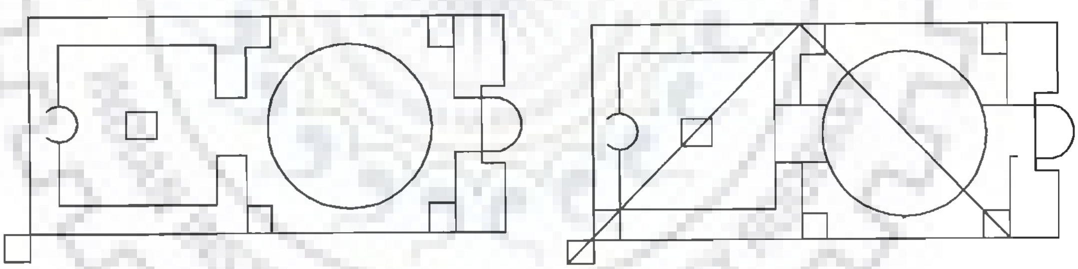
The spaces are grouped in the form of cluster with dominating linearity. The main circular space is surrounded within square interior. The building is



Plan



Section Geometry



Plan Geometry

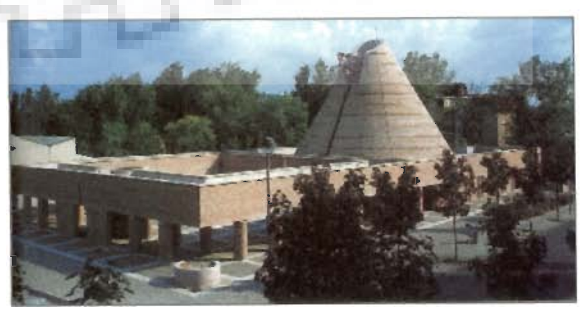


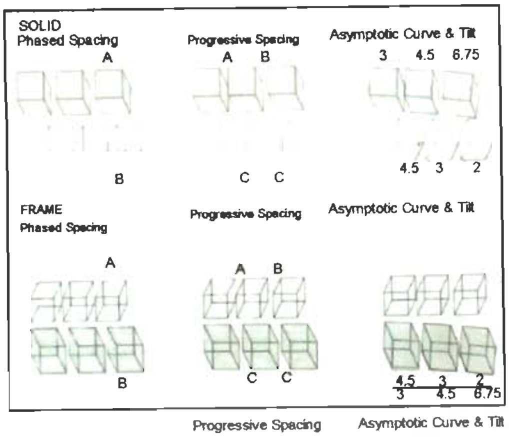
Fig 5.38 GEOMETRICAL ANALYSIS - CHURCH OF BEATO ODORICO
Clark & Pause (1996)

approached obliquely from outside with linear movement pattern inside passing through different spaces terminating in the main space. Building gains visual weight mainly due to massing, red color and brick textured surfaces. It satisfies both visual as well as human scale. The structure is compressive in the central conical shell and flexural in the remaining parts. Spherical as well as rigid right angled load transfer is witnessed. The structure is safe primarily because of regularity and symmetry. Reinforced concrete is the main structural material. Natural light articulates the interior directly and indirectly through roofs.

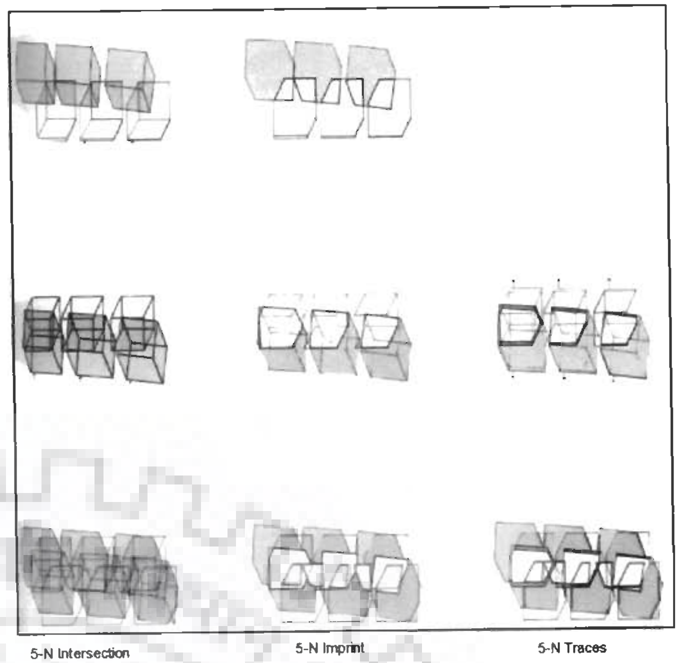
5.39. CARNEGIE MELLON RESEARCH INSTITUTE : PENNSYLVANIA (1989 AD)

Designed by Peter Eisenman, it was conceptualized to represent man's overcoming the natural system in this era. He conceptualized it in the form of combination of modules of Boolean cube in solid and in hollow frames which make it a complex structure positioned between the purity of a platonic form and the infinite and unlimited form of non-Euclidean structure. This exhibits the properties of platonic forms when frozen. The building is made up of pairs of Boolean cubes with each pair contains two solid cubes and two frame cubes. Each pair contains the inverse of the other as solid and void. The pairs are continuously and progressively spaced so that a sine curve is generated due to phased spacing and asymptotic curves of the cubes.

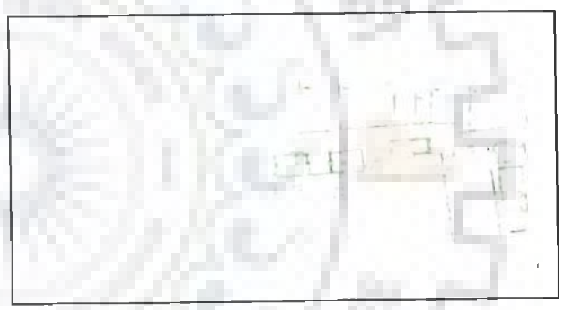
The modules in the form of cubes are added to give it a final form which is linear and clustered with similar spatial organization having



Conceptual Geometry



First Level Plan

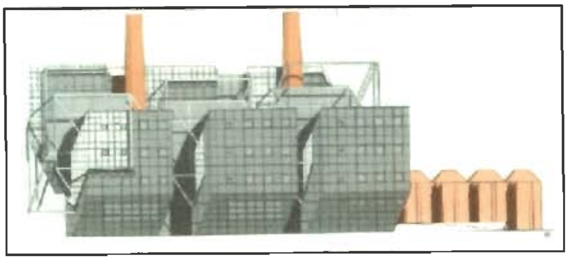


Second Level Plan

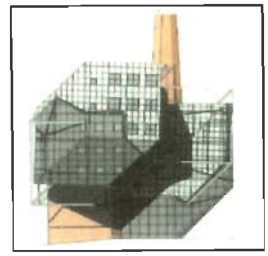
Fifth Level Plan

Sixth Level Plan

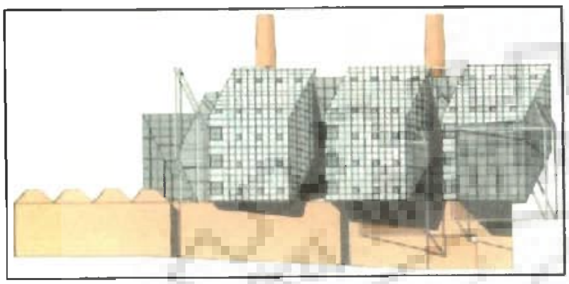
Fig 5.39 (a) GEOMETRICAL ANALYSIS - CARNEGIE MELLON RESEACH INSTITUTE
Eisenman Architects (1989)



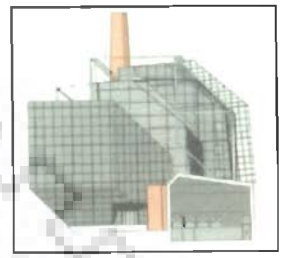
North Elevation



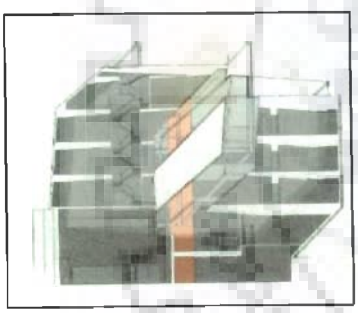
West Elevation



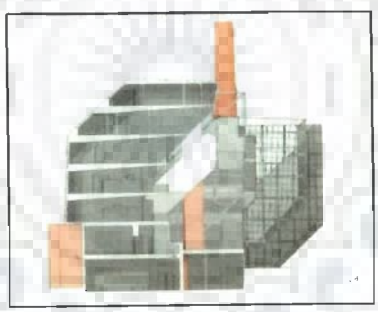
South Elevation



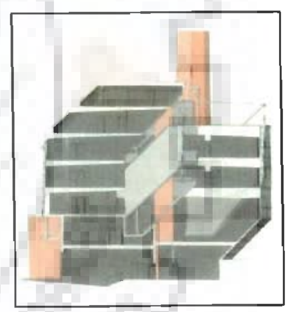
East Elevation



Section AA



Section BB



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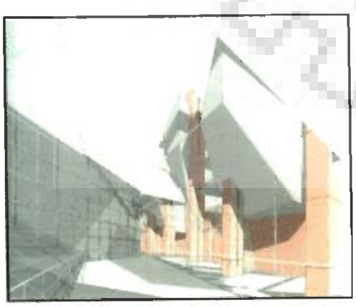
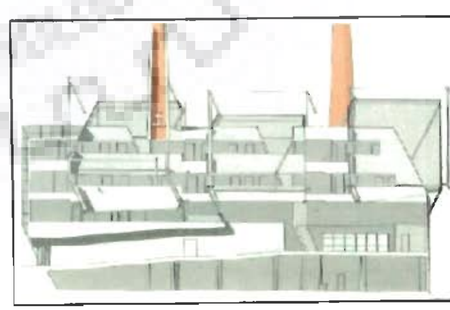


Interior Perspective



Section DD

Fig 5.39 (b) GEOMETRICAL ANALYSIS - CARNEGIE MELLON RESEACH INSTITUTE
Eisenman Architects (1989)

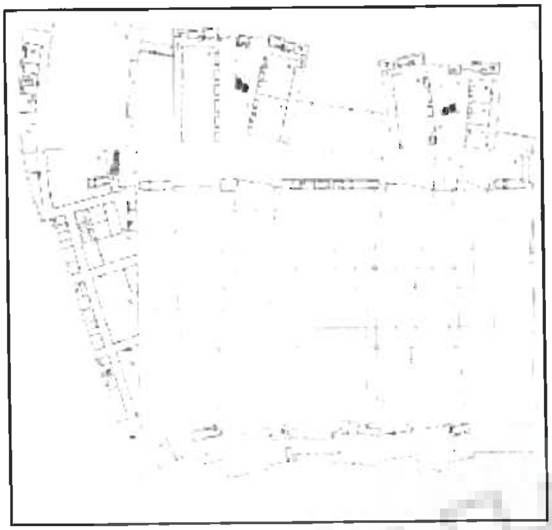
combination of interlocked spaces at some junctures, while other spaces are simply placed to be linked by common space.

The building owing to its design philosophy does not possess any axiality, symmetry and hierarchy in it. It is approached obliquely from outside with linear movement pattern inside. Because of dramatic massing, emphasized corners and surface articulation it gains strong visual weight. The building is a combination of spherical, diagonal and spatial structural systems of load transfer with an integration of shell system, plate system and space-frames. It is safe from earthquake because of controlled ratios among different dimensions of length, breadth and height. RCC and steel are the main structural materials. Natural light enters directly from walls and roof.

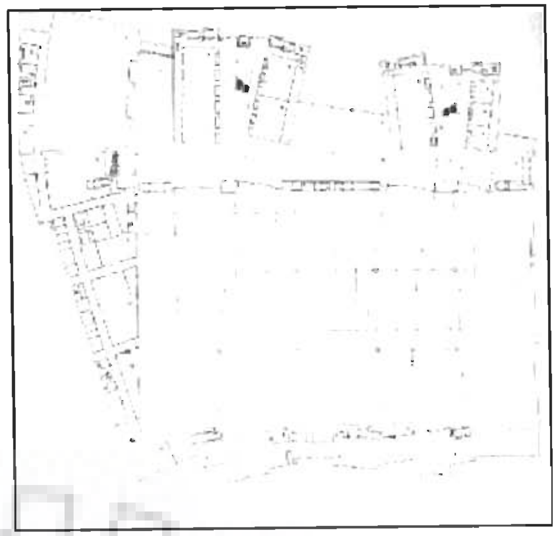
5.40. COLUMBIA CONVENTION CENTER : COLUMBUS (1989-1993 AD)

Designed by Peter Eisenman, it constitutes the next generation of experiments. The spirit of new and existing time is the symbol of light determines the main concept of this form. Eisenman created a conduit between the Ohio center and the surrounding neighborhoods. The asymmetrical building with exterior iconography suggested movement and dynamism. The curving forms suggest roads, railways or fiber-optic cables. These forms terminate in an angular façade of rectangular blocks.

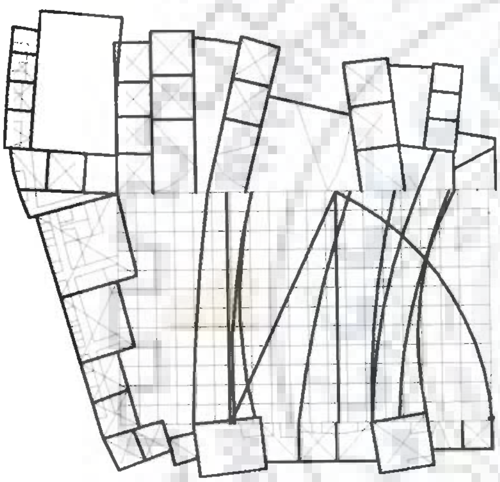
Though seems complex, the form is again based on golden and geometrical proportions to fulfill its spirit of new time and to achieve functional efficiency. The form is centralized with double-height central space. The parts are otherwise arranged in a clustered form with similar spatial organization having main interlocking spaces and secondary spaces linked by common space. The building has frontal and oblique approach with linear movement



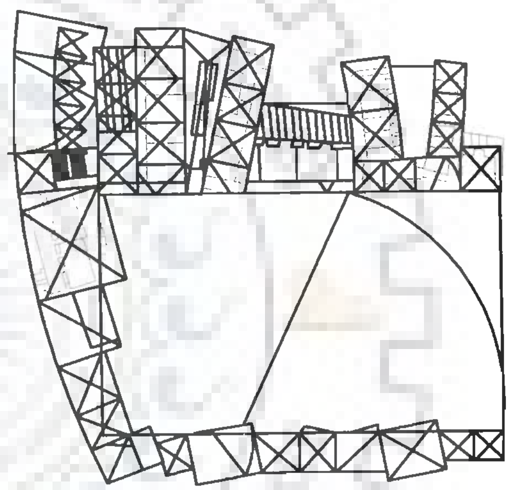
Ground Floor Plan



Mezzanine Floor Plan



Geometrical Analysis of
Ground Floor Plan



Geometrical Analysis of
Mezzanine Floor Plan

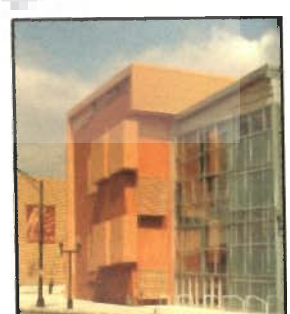
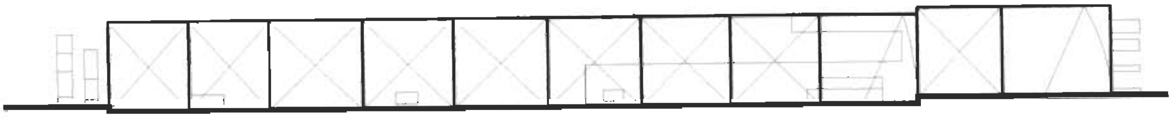
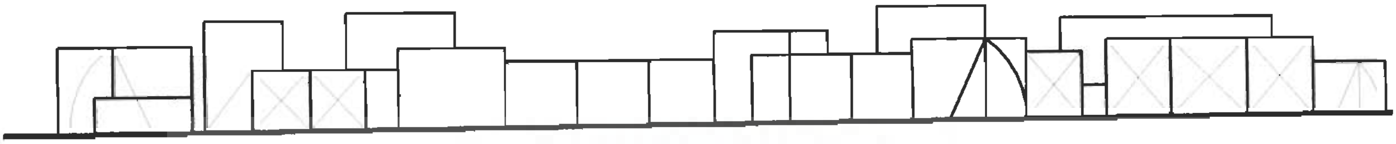


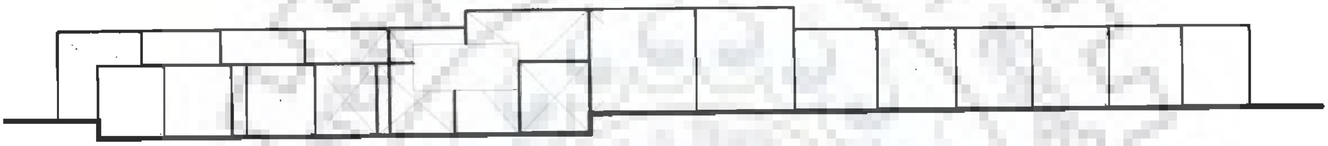
Fig 5.40 (a) GEOMETRICAL ANALYSIS - COLUMBIA CONVENTION CENTER
Ekta Mehta (2001)



North Elevation



Main Elevation (West)



South Elevation

East Elevation

Elevational Geometry

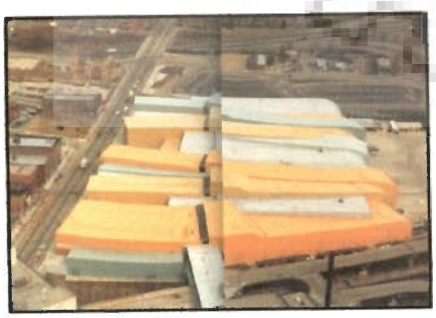


Fig 5.40 (b) GEOMETRICAL ANALYSIS - COLUMBIA CONVENTION CENTER

Ekta Mehta (2001)

pattern inside with main path moves around central space. Because of tangled curving, multicolored roof planes, textured surfaces, the building acquires strong visual weight. The scale responds both to human being and inherent order in the composition with average co-operation among different parts. The structure is flexural with rigid right angled RCC frame for load transfer. The building exhibits earthquake safety because of controlled ratios among different dimensions of length, width and height. Direct natural light enters through roof and wall surfaces.

CHAPTER 6

DATA PREPARATION AND STATISTICAL ANALYSIS

6.0. INTRODUCTION

The purpose of this research is to formulate a rational and logical approach for the application of geometry in architecture taking into consideration all the aspects with which geometry is found to be related. The necessary control parameters under each aspect are brought together to comprehend and analyze existing buildings and to formulate our proposal according to the objectives framed. This part concentrates upon three systematic frameworks - data preparation for the evaluation of forty selected buildings against each of the control parameters, determination of significant control parameters in respect of each of the six geometrical systems followed by theoretical model for each of the geometrical systems separately for appraisal of existing buildings and for programming of proposed ones.

6.1. METHODOLOGY AND TECHNIQUES USED

First of all, the six types of geometrical systems identified in the making of architectural form, called dependent variables, are listed. Different architectural aspects like symbolic and visual references, form, space, articulation, and structure with their respective subparts were put forth. Detailed control parameters, called independent variables, under each element and its subparts are placed. In all, 6 dependent and 98 independent variables are determined.

Dichotomous data in respect of both dependent and independent variables in the form of ‘0’ and ‘1’ is generated, where ‘0’ represents the absence of any particular variable while '1' refers to its presence against each of the forty buildings. An attempt is thus made to present information qualitative in nature into quantitative dichotomous form.

The data thus generated is analyzed with optimal statistical tools and techniques such as Gamma Coefficient of Association for Ordinal Variables for the determination of significant control parameters in respect of each system followed by the application of logistic regression with which models are generated in order to predict the collective contribution of significant control parameters toward their respective geometrical systems separately.

The fitted equation of logistic regression model is given by

$$P(X) = \frac{1}{1 + e^{-y}}$$

Where

$P(x)$ = probability of prediction based on independent variables and

$Y = a_0 + a_1x_1 + a_2x_2 + a_3x_3 + \ldots\ldots\ldots\ldots a_k x_k$

Where $a_0, a_1, a_2, a_3 \ldots a_k$

are constants and can be estimated by using method of maximum likelihood from the given data,

$X_1, X_2, X_3 \ldots\ldots\ldots X_k$

are the respective independent variables /control parameters which are involved in the probability of prediction, their value will be either 'O' or '1' depending upon their respective absence or presence in any building where the model is applied,

and e, the base of natural logarithm = 2.7183

6.2. FORMULATION OF CONTROL PARAMETERS

To determine the relevance of geometry in architecture, first of all the major elements that collectively contribute in the making of architecture were identified and then were broken down to their sub-parts, which in turn have further subdivisions which are designated here as control parameters. These elements are qualitative as well as quantitative in nature. Extensive use of available literature has been made to first determine the main elements followed by the formulation of control parameters under each one of them.

Based on the literature discussed, geometry is found to be strongly related to the following architectural elements:

i) Symbolic and visual references

ii) Form

iii) Space

iv) Circulation

v) Articulation

vi) Structure

Out of which the later four are further subdivided into sub-parts as given below: -

Geometry as Space

- Spatial organization
- Spatial relationships
- Ordering principles

Geometry as Circulation

- Approach
- Configuration of the path
- Path space relationship

Geometry as Articulation

- Corners
- Surface Properties
- Scale

Geometry as Structure

- System of Loading
- Types of Load Transmission
- Lateral Loads
- Structural Material
- Material Properties
- Standardization
- Natural Light

	LIST OF GEOMETRICAL SYSTEMS	ABBREVIATIONS AS USED IN ANALYSIS AND MODEL
1	MATHEMATICAL PROPORTIONS	MATH_PRO
2	GOLDEN PROPORTIONS	GOLDEN
3	GEOMETRICAL PROPORTIONS	GEO_PRO
4	REGULATING LINES	REG_LINE
5	MODULE-BASED PROPORTIONS	MOD_BASE
6	PREFERRED DIMENSIONS	PREF_DIM

	DETAILED LIST OF OVERALL CONTROL PARAMETERS	ABBREVIATIONS AS USED IN ANALYSIS AND MODEL
1.	**SYMBOLIC AND VISUAL REFERENCES**	
i)	Timelessness (Mythological, Religious, Cultural)	TIMELESS
ii)	Visual (Regulating Lines, Le-Modular etc.)	VISUAL
iii)	Functional	FUNCTION
iv)	Timeboundedness (PoMo, De-Con, Futuristic etc.)	TIMEBND
2.	**FORM**	
i)	Regular	REG_FORM
ii)	Additive	ADD_FORM
iii)	Subtractive	SUB_FORM
iv)	Centralized	CEN_FORM
v)	Linear	LIN_FORM
vi)	Radial	RAD_FORM
vii)	Clustered	CLS_FORM
viii)	Grid	GRD_FORM
3.	**SPACE**	
3.1	**Spatial Organization**	
i)	Centralized	CEN_SPO
ii)	Linear	LIN_SPO
(iii)	Radial	RAD_SPO
(iv)	Clustered	CLS_SPO
(v)	Grid	GRD_SPO
3.2	**Spatial Relationships**	
i)	Space within a space	SWS_SR
ii)	Interlocking Space	IS_SR
iii)	Adjacent Spaces	AS_SR
iv)	Spaces Linked by Common Space	SLBCS_SR

3.3	**Ordering Principles**	
i)	Axis	AX_OP
ii)	Symmetry	SYM_OP
iii)	Hierarchy	HIE_OP
iv)	Datum	DAT_OP
v)	Rhythm	RHY_OP
vi)	Repetition	REP_OP
vii)	Transformation	TRANS_OP
4.	**CIRCULATION**	
4.1	**Approach**	
i)	Frontal	FR_APP
ii)	Oblique	OB_APP
iii)	Spiral	SP_APP
4.2	**Configuration of the Path**	
i)	Linear	LIN_CP
ii)	Radial	RAD_CP
iii)	Spiral	SP_CP
iv)	Grid	GRD_CP
v)	Network	NET_CP
vi)	Composite	COMP_CP
4.3.	**Path Space Relationship**	
i)	Pass By Spaces	PBS_PSR
ii)	Pass Through Spaces	PTS_PSR
iii)	Terminate in a Space	TIS_PSR
5.	**ARTICULATION**	
5.1	**Corners**	
i)	Emphasized	EMP_COR
ii)	Continuous/Smooth	C_SM_COR
5.2	**Surface Properties**	
5.2.1	***Visual Weight Due To***	
i)	Texture	TEX_VW
ii)	Color	COL_VW

iii)	Optical Patterns	OPT_VW
iv)	Massing	MASS_VW
5.2.2	***Scale***	
i)	Visual Scale	VIS_SC
ii)	Human Scale	HUM_SC
5.2.2.1	***Hierarchical Co-Operation of Different Scales***	
(i)	Good	GO_HCDS
(ii)	Average	AV_HCDS
(iii)	Poor	PO_HCDS
6.	**STRUCTURE**	
6.1	**System of Loading**	
	Gravity Loads (Predominant Stresses)	
i)	Compression	COM_GL
ii)	Tension	TEN_GL
iii)	Flexural	FLEX_GL
6.2	**Type of Load Transmission System**	
6.2.1	***Right Angled***	
i)	Right Angled Load Transmission	RALT
ii)	Non-rigid Right Angled System	NIRRAS
iii)	Rigid Right Angled System	RRAS
6.2.2	***Spherical Load Transmission***	
i)	Arch System	ARC_SL
ii)	Vaulting	VLT_SL
iii)	Dome	DOM_SL
iv)	Shell System	SHEL_SL
6.2.3	***Diagonal Load Transmission***	
i)	Truss System	TRS_DLT
ii)	Plate System	PS_DLT
6.2.4	***Spatial Load Transmission***	
i)	Space Structure	SPST_SLT
ii)	Space Frame Combinations	SFC_SLT

6.3	**Lateral Loads (EQ Loads)**	
6.3.1	***Plan Configuration***	
i)	Regular	REG_PCEQ
ii)	Symmetrical	SYM_PCEQ
6.3.2	***Elevation***	
i)	Regular	REG_ELEQ
ii)	Symmetrical	SYM_ELEQ
6.3.3	***L/W Ratio* (from 1:1-1:2)**	**LWR_EQ**
6.3.4	***H/B Ratio* (H-3-4W)**	**HBR_EQ**
6.3.5	***Weight***	
	Light Weight	LW_EQ
6.3.6	***Safety Due to Strength, Stiffness, Ductility***	**SSSD_EQ**
6.3.7	***Relationship of Structural and Non Structural Components***	
	Effective Integration of the Two	EIT_SNSC
	Proper Isolation of the Two	PIT_SNSC
6.4	**Structural Material**	
i)	Wood/Timber	WD
ii)	Brick	BK
iii)	Concrete	CONC
iv)	R.C.C.	RCC
v)	Steel	STL
vi)	Stone	STON
vii)	Iron	IRON
viii)	Any Other	ANYOTH

6.5	**Material Properties**	
6.5.1	***Durability***	**DUR**
6.5.2	***Material / Space Ratio***	
i)	High	HIGH_MSR
ii)	Low	LOW_MSR
iii)	Local Availability	LOC_AV
6.6	**Standardization**	
	Use of	
i)	Absolute Measures (Modular Co-ordination)	ABS_M_ST
ii)	Relative Measures	REL_M_ST
iii)	Preferred Measures (Le-Modular)	PRF_M_ST
6.7	**Natural Light**	
i)	Direct Through Walls	NL_DW
ii)	Direct Through Roof	NL_DR
iii)	Indirect Through Walls	NL_INDW
iv)	Direct Through Roof	NL_INDR
v)	Diffused Through Walls	NL_DGW
vi)	Diffused Through Roof	NL_DFR
vii)	Open to Sky Space	NL_OTSS

6.3. MATHEMATICAL PROPORTIONS

To find the association between Mathematical Proportions with the independent variables (control parameters), Gamma co-efficient of Association for Ordinal Variables was computed and it has been found that out of total 98 independent variables, following 27 are significantly related with this dependent variable:

TIMEBND, CEN_FORM, LIN_FORM, CEN_SPO, LIN_SPO, AS_SR, FR_APP, OB_APP, PTS_PSR, TIS_PSR, AX_OP, HIE_OP, COM_GL, FLEX_GL, RALT, RRAS, DOM_SL, SHEL_SL, TRS_DLT, LW_EQ, PIT_SNSC, RCC, DUR, REL_M_ST, PRF_M_ST, NL_DW, NL_OTSS

Furthermore, logistic regression model was applied and the following equation was obtained for Mathematical Proportions:

$$P(x) = \frac{1}{1+e^{-y}}$$

Where

Y = -148.209 – 26.745 TIMEBND – 54.519 CEN_FORM- 3.054 CEN _ SPO + 16.271 LIN _SPO + 9.570 FR_APP + 46.633 OB_APP+ 4.221 PTS_PSR + 21.329 AX_OP + 12.376 HIE_OP + 137.757 FLEX_GL- 36.091 RALT + 86.003 DOM_SL – 28.830 SHEL_SL – 85.099 RCC+ 41.304 REL_M_ST + 98.209 PRF_M_ST – 1.936 NL_DW+ 6.215 LIN_FORM – 36.935 AS_SR + 31.951 TIS_PSR + 14.095 COM_GL – 31.833 RRAS + 37.569 TRS_DLT + 101.896 LW_EQ – 59.333 PIT_SNSC + 46.545 DUR + 84.336 NL _ OTSS

and e = 2.7183

The framed model can predict with 100% authenticity when applied on any new case as classified by logistic regression.

6.4. GOLDEN PROPORTIONS

The computation of Gamma co-efficient of Association in this case has shown that the following 18 independent variables are significantly related with Golden Proportions:

VISUAL, ADD_FORM, AS_SR, REP_OP, EMP_COR, TEX_VW, MASS_VW, VIS_SC, RALT, VLT_SL, DOM_SL, LW_EQ, EIT_SNSC, STON, REL_M_ST, NL_DR, NL_INDR, NL_OTSS.

The application of logistic regression resulted in the following equation for Golden Proportions:

$$P(X) = \frac{1}{1+e^{-y}}$$

Where

Y = 126.318 + 3.993 VISUAL – 86.114 ADD_FORM + 10.066 AS_SR + 52.782 REP_OP + 54.633 EMP_COR – 50.688 TEX_VW – 21.432 MASS_VW – 158.093 VIS_SC – 11.864 RALT – 10.066 VLT_SL – 21.761 DOM_SL – 21.386 LW_EQ + 133.233 EIT_SNSC – 54.633 STON+169.415 REL_M_ST – 67.577 NL_DR – 10.427 NL_INDR + 4.063 NL_OTSS

and e = 2.7183.

The obtained model can predict with 92.5% accuracy when applied on any other building as classified by logistic regression.

6.5. GEOMETRICAL PROPORTIONS

Following 22 independent variables out of the total 98 ones are found to be significantly associated with Geometrical Proportions by the computation of Gamma co-efficient of Association:

TIMELESS, FUNCTION, CEN_SPO, CLS_SPO, RAD_CP, PBS_PSR, PTS_PSR, TIS_PSR, SYM_OP, REP_OP, OPT_VW, TEN_GL, ARC_SL, DOM_SL, SYM_PCEQ, SYM_ELEQ, LWR_EQ, EIT_SNSC, CONC, IRON, LOC_AV, NL_INDR

The application of logistic regression resulted in the following equation for Geometrical Proportions:

$$P(X) = \frac{1}{1+e^{-y}}$$

Where

Y = 133.055 – 71.686 TIMELESS + 1.109 FUNCTION – 37.649 CEN_SPO – 36.755 CLS_SPO + 5.140 RAD_CP + 4.372 PBS_PSR – 39.879 PTS_PSR + 73.131 TIS_PSR + 1.660 SYM_OP – 6.093 REP_OP + 2.902 OPT_VW + 69.760 TEN_GL + 68.418 ARC_SL + 1.908 DOM_SL + 31.720 SYM_PCEQ – 29.736 SYM_ELEQ + 17.372 LWR_EQ – 56.120 EIT-SNSC + 35.189CONC + 5.928 IRON – 37.099 LOC_AV – 21.139 NL_INDR

and e = 2.7183

The framed model can predict with 100% authenticity when applied on any other building as classified by logistic regression.

6.6. REGULATING LINES

Gamma co-efficient of association in the case of regulating lines has resulted in the following 19 independent variables which are significantly related with this dependent variable:

TIMELESS, VISUAL, CEN_FORM, LIN_SPO, IS_SR, PTS_PSR, TIS_PSR, REP_OP, HUM_SC, GO_HCDS, AV_HCDS, COM_GL, RALT, NRRAS, RRAS, LWR_EQ, STL, IRON, NL_DFW, NL_OTSS

The application of logistic regression has given us the following equation of Regulating Lines:

$$P(x) = \frac{1}{1+e^{-y}}$$

Where

Y = 15.602 + 13.255 TIMELESS + 13.232 VISUAL + 26.474 CEN_FORM – 23.935 LIN_SPO + 24.854 IS_SR + 50.834 PTS_PSR – 27.418 TIS_PSR + 1.128 HUM_SC – 28.806 GO_HCDS – 68.725 AV_HCDS – 35.842 RALT – 10.436 LWR_EQ – 73.644 STL – 73.691 IRON + 1.962 NL_DFW – 13.935 NL_OTSS – 46.896 REP_OP + 23.635 COM_GL + 1.930 RRAS

and e = 2.7183

The framed model can predict with 100% accuracy when applied on any other building as classified by logistic regression.

6.7. MODULE BASED PROPORTIONS

As has been found through of computation of Gamma co-efficient of Association, following 14 independent variables are found to be significantly associated with Module Based Proportions as given below:

TIMEBND, LIN_FORM, LIN_CP, PBS_PSR, REP_OP, TEX_VW, HUM_SC, ARC_SL, EIT_SNSC, PIT_SNSC, STON, ABS_M_ST, PRF_M_ST, NL_OTSS

The following equation was obtained for Module Based Proportions on the application of logistic regression:

$$P(X) = \frac{1}{1+e^{-y}}$$

Where

Y = 40.673 – 36.049 TIMEBND + 86.348 LIN_FORM+ 17.129 LIN_CP + 48.086 PBS_PSR – 4.728 REP_OP- 42.522 TEX_VW + 33.213 HUM_SC + 21.674 ARC_SL- 70.789 EIT_SNSC – 72.593 PIT_SNSC + 35.631 STON + 2.931 ABS_M_ST – 13.094 PRF_M_ST – 45.257 NL_OTSS

and e = 2.7183

The framed model can predict with 97.5% authenticity when applied on any other building.

6.8. PREFERRED DIMENSIONS

Gamma co-efficient of Association was computed for this dependent variables and it has been found that following 25 out of total 98 independent variables are significantly related with Preferred Dimensions:

TIMELESS, VISUAL, FUNCTION, TIMEBND, ADD_FORM, CEN_FORM, CEN_SPO, IS_SR, C_SM_COR, TEX_VW, OPT_VW, MASS_VW, HUM_SC, GO_HCDS, AV_HCDS, RRAS, DOM_SL, TRS_DLT, LW_EQ, RCC, STL, STON, DUR, REL_M_ST, NL_INDW

Logistic regression model was applied and the following equation was obtained for Preferred Dimensions:

$$P(X) = \frac{1}{1+e^{-y}}$$

Where

Y = - 91.176 – 8.107 TIMELESS + 31.538 VISUAL + 9.120 FUNCTION – 3.336 TIMEBND – 20.322 ADD_FORM – 22.731 CEN_FORM – 1.067 CEN_SPO+29.024 IS_SR – 3.174 C_SM_COR – 2.382 TEX_VW + 30.757 OPT_VW + 64.977 MASS_VW+ 4.542 HUM_SC – 72.003 GO_HCDS – 77.222 AV_HCDS + 0.591 RRAS+ 20.749 DOM_SL + 23.282 TRS_DLT + 32.041 LW_EQ + 39.768 RCC + 6.806 STL + 18.340 STON + 15.002 REL_M_ST–1.788 DUR + 1.196 NL_INDW

and e = 2.7183

The obtained model can predict with 100% accuracy when applied on any other building.

TEST APPLICATION ON SELECTED BUILDINGS

7.0. INTRODUCTION

The test application of the model developed for different geometrical systems in chapter 6 will determine its usefulness in contemporary architecture. For this purpose, following three buildings from the second half of the 20th century, designed by three different architects have been selected:

(i) Salk Institute of Biological studies: La Jolla, California (1959-65 AD)

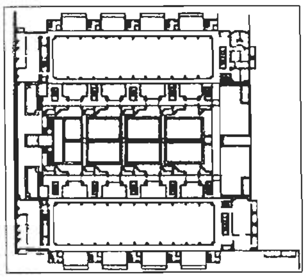
(ii) Smith House: Darien, Connecticut (1965-67AD)

(iii) Olivetti Training Center, Haslemere, Surrey, England (1969AD)

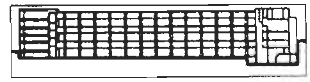
7.1. SALK INSTITUTE OF BIOLOGICAL STUDIES, : LA JOLLA, CALIFORNIA (1959-65AD)

These research laboratories and offices, designed by Louis. I. Kahn, house ducts in the hollows of box girders and vented from huge hoods at the flanks of the building. The building basically comprises of two parallel laboratories encircled by corridor flanking a central court. The offices and study areas for scientists are placed on the outer periphery of the corridor receiving views of the ocean by virtue of exterior walls angled towards it.

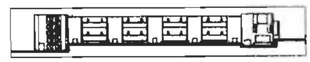
Geometrical proportions in the form of square and $\sqrt{2}$ rectangle create the basis of the architectural form for aesthetic and functional reasons. The form is composed of additions of different units creating centralized and linear spatial organization. The building is approached frontally from outside. The spaces are placed adjacent to each other linked by common linear space of



Plan

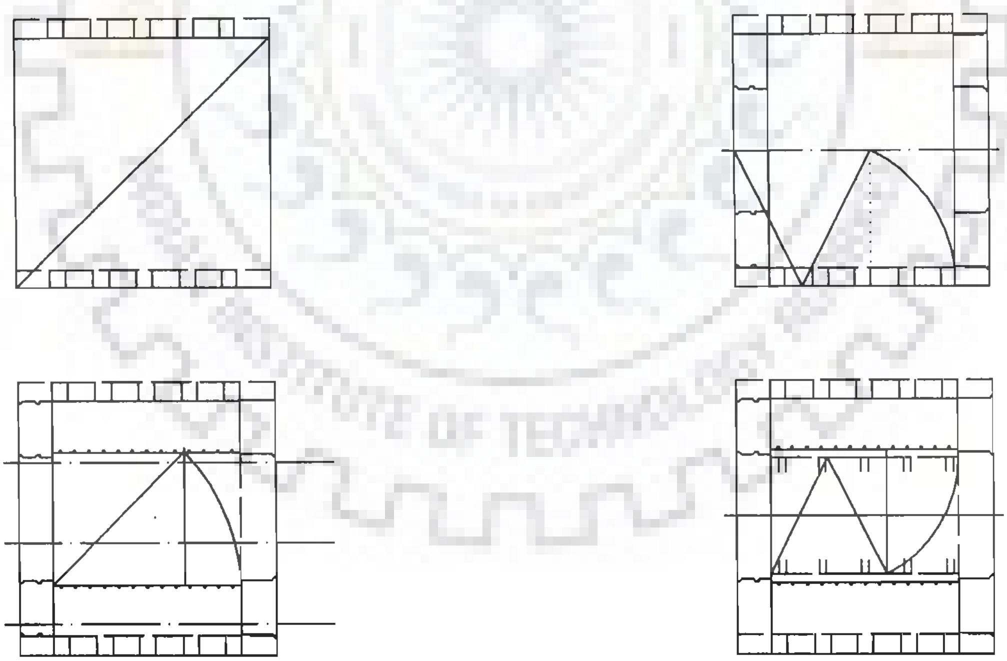


Cross Section



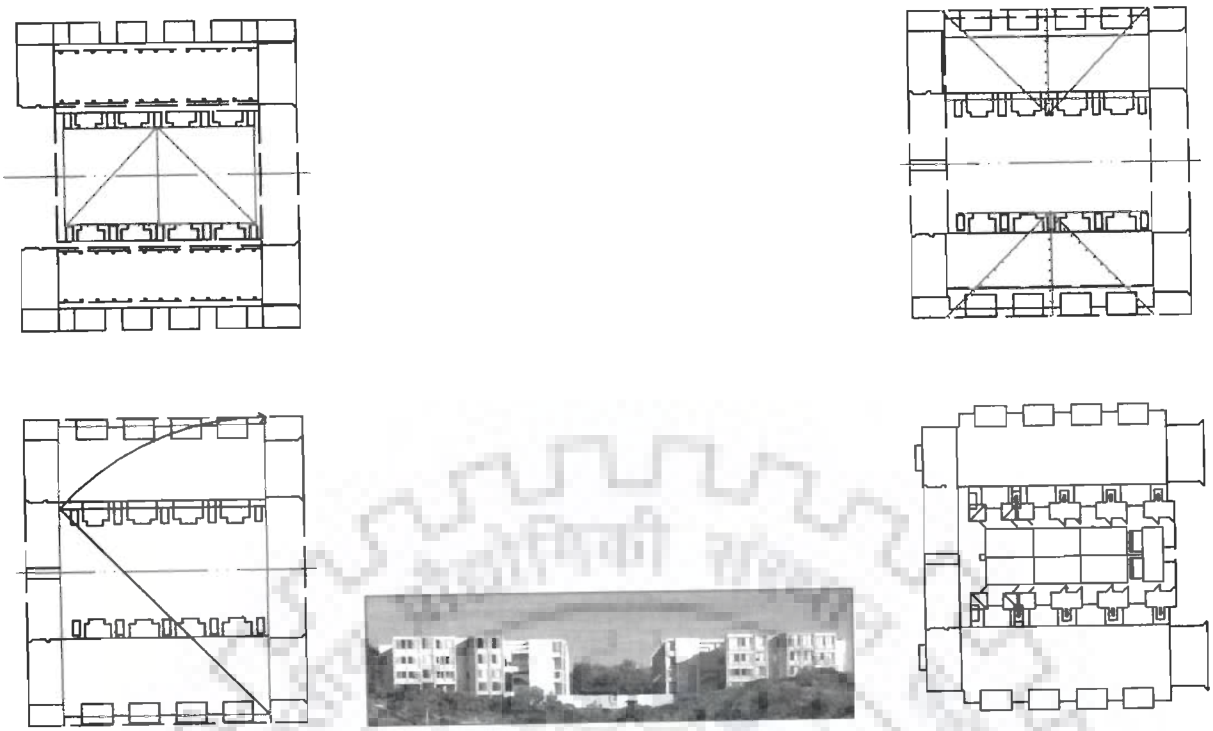
Elevation

Plan Geometry (Clark & Pause , 1996)



Development of Plan From Square (Gast , 1998)

Fig7.1 (a) GEOMETRICAL ANALYSIS - SALK INSTITUTE FOR BIOLOGICAL STUDIES



Plan Geometry in The Final Shape (Gast , 1998)

Symmetry

Addition And Subtraction
(Clark & Pause , 1996)

Fig7.1 (b) GEOMETRICAL ANALYSIS - SALK INSTITUTE FOR BIOLOGICAL STUDIES

the corridor. The building has strong visual weight due to emphasized corners, massing, and textured surface of exposed concrete joints with optical pattern creating interest. It is safe from earthquake due to symmetry and controlled ratios between length, breadth and height. This RCC structure is flexural in nature with rigid right angled load transfer system.

Out of the significant control parameters associated with geometrical proportions, the following are present in this building.

FUNCTION, CEN_SPO, PBS_PSR, SYM_OP, REP_OP, OPT_VW, TEX_VW, SYM_PCEQ, SYM_ELEQ, LWR_EQ, EIT_SNSC, LOC_AV

Substituting the dichotomous values in logistic regression model for this geometrical system, we get: -

$$P(X) = \frac{1}{1 + e^{-y}}$$

where y = 133.055 – 71.686 (0) + 1.109 (1) – 37.649 (1) – 36.755 (0) + 5.140 (0) + 4.372 (1) – 39.879 (0) + 73.131 (0) + 1.660 (1) – 6.093 (1) + 2.902 (1) + 69.760 (0) + 68.418 (0) + 1.908 (0) + 31.720 (1) – 29.736 (1) + 17.372 (1) – 56.120 (1) + 35.189 (0) + 5.928 (0) – 37.099 (1) – 21.139 (0)

$\Rightarrow$ y = 25.493, therefore P (X) =1

The value of P (X) as '1' indicates that the validity of model for this building is 100%. The significant control parameters associated with geometrical proportions and are present in this building perfectly contribute in incorporating this geometrical system in this building.

7.2. SMITH HOUSE : DARIEN, CONNECTICUT (1965-67 AD)

Designed by Richard Meier, this house is located on the shore and is approached through ramp reaching directly to the second floor. The building is RCC structure with white exterior and vast plate glass windows towards the

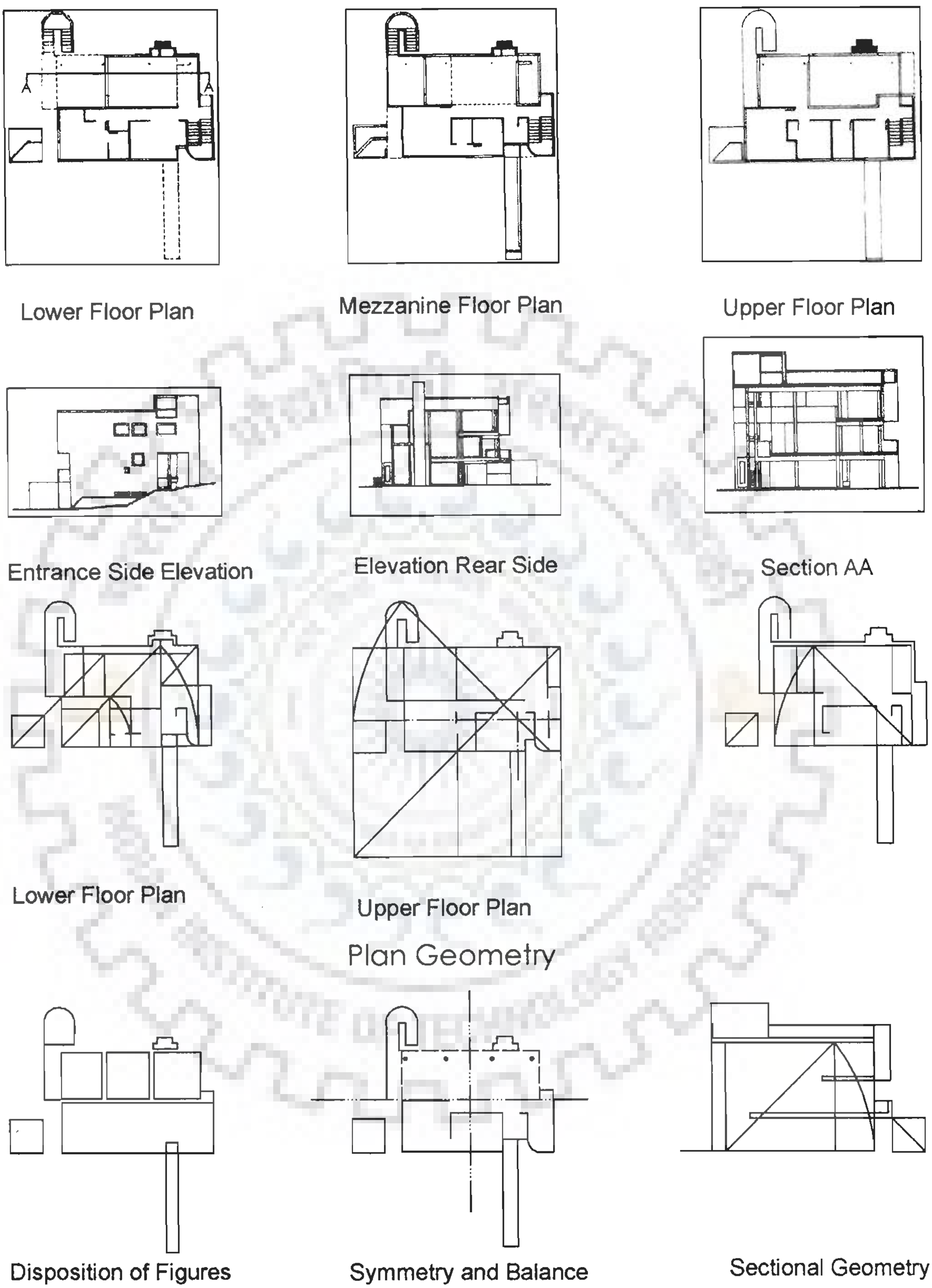


Fig 7.2 GEOMETRICAL ANALYSIS - SMITH HOUSE
Clark & Pause (1996)

shore and solid façade towards the entrance side. The living areas and terraces open to water-front view. The house responds to the rhythms of slope, trees, rock and shore line.

This building is an example of late modernism. It has employed geometrical proportions in its composition for aesthetic and functional reasons. It is regular in form with centralized spatial organization having interlocking spaces inside the cubical volume. The building has frontal approach with linear movement pattern inside. The visual weight is due to surface articulation and sculptural massing. This RCC structure is subjected to flexural loading with rigid right angled load transfer.

The following significant parameters associated with geometrical proportions are found to be present in this building.

FUNCTION, CEN_SPO, SYM_OP, REP_OP, PBS_PSR, OPT_VW, LWR_EQ, EIT_SNSC, LOC_AV.

Substituting the dichotomous values to the logistic regression model for this geometrical system, we get:

$$P(X) = \frac{1}{1+e^{-y}}$$

where y = 133.055 – 71.686 (0) + 1.109 (1) – 37.649 (1) –36.755 (0) + 5.140 (0) + 4.372 (1) – 39.879 (0) + 73.131(0) + 1.660 (1) – 6.093 (1) + 2.902 (1) + 69.760 (0) + 68.418 (0) + 1.908 (0) + 31.720 (0) – 29.736 (0) + 17.372 (1) – 56.120 (1) + 35.189 (0) + 5. 928 (0) – 37.099 (1) – 21.139 (0)

$\Rightarrow$ y = 23.509, and thus P (X) = 1.

The value of P (X) as '1' indicates that the validity of model for this building is 100%. The significant control parameters associated with geometrical proportions and are present in this building perfect contribute in incorporating this geometrical system is this building

7.3. OLIVETTI TRAINING CENTER : HASLEMERE, ENGLAND (1969 AD)

Designed by James Stirling, the building is essentially linear in organization due to the repetitive addition of modular limits. The building has incorporated golden proportions in its composition because of aesthetic and functional criteria. The spatial organization is linear with different spaces placed adjacent to each other linked by common circulation area. It is approached obliquely from outside with linear movement pattern inside. The order is achieved through good co-operation among different scales. The structure is flexural with rigid right angled load transfer. Due to rigidity it is safe from earthquake. Natural light in direct and indirect form enters through roof and wall surfaces. Following. significant parameters associated with golden proportions are found to be present here:

VISUAL, ADD_FORM, AS_SR, REP_OP, VIS_SC, EIT_SNSC, NL_DR, NL_INDR.

Substituting the values of the logistic regression model for this geometrical system, we get: -

$$P(X) = \frac{1}{1+e^{-y}}$$

where y = 126.318 + 3.993 (1) – 86.114 (1) + 10.066 (1) + 52.782 (1) + 54.633 (0) – 50. 688 (0) – 21.432 (0) – 158.093 (1) – 11.864 (0) – 10.066 (0) – 21.761 (0) – 21.386 (0) + 133.233 (1) – 54.633 (0) + 169.415 (0) – 67.577 (1) – 10.427 (1) + 4.063 (0)

$\Rightarrow$ y = 4.181 and therefore, P (X) = 0.985

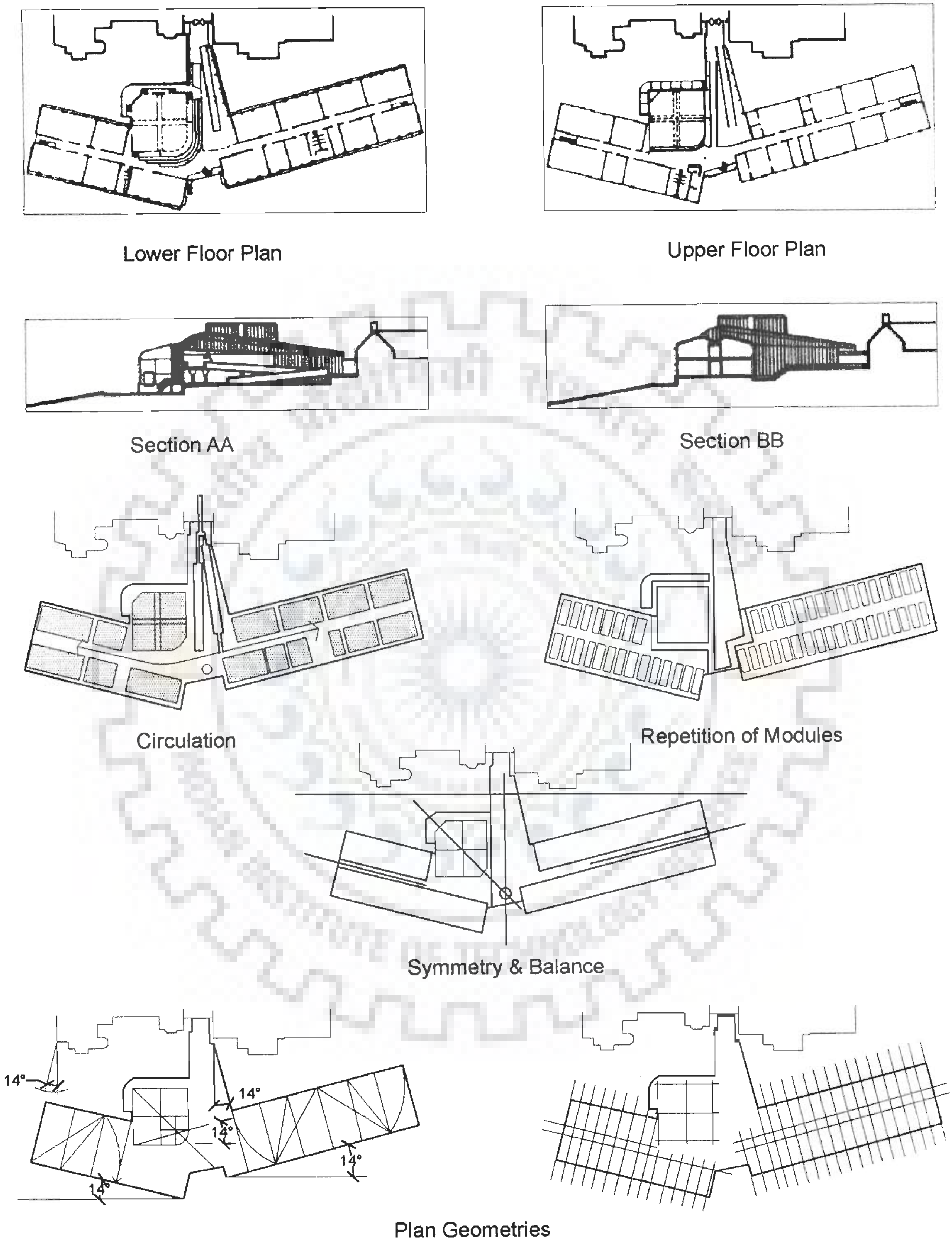


Fig 7.3 GEOMETRICAL ANALYSIS - OLIVETTI TRAINING CENTER
Clark & Pause (1996)

The value of P (X) as 0.985 indicates that the validity of model for this building is 98.5%. The contribution of those significant control parameters associated with golden proportions and are present in this building is extremely high in incorporating this geometrical system in this building.

The above three cases illustrated in this chapter discuss the applicability of only two of the six logistic regression models explained in chapter 6. However the validity of the remaining four models for each of the respective geometrical system can also be verified in this way.

The validity of these logistic regression models in the above three cases prove the importance of formulated scientific basis for the application of these respective geometrical systems in the creation of holistically meaningful architecture.

CONCLUSIONS

8.0. INTRODUCTION

To understand the relevance of geometry in architecture through the analysis of available literature mentioned in chapters 2,3 and 4 followed by the systematic investigation of the selected case-studies discussed in chapters 5 and 6, set of conclusions have been framed.

The conclusions based on the analysis of literature (discussed under appropriate heads), the investigation of case-studies through statistical techniques culminating in form of model, elaborate on the relevance of geometry and discuss the application part of each of the geometrical systems, separately, in architecture. Based on these conclusions, geometry, in the form of these systems, can be applied in architecture by contemporary architects to create a holistically meaning environment.

8.1. CONCLUSIONS

8.1.1. Importance of Geometry

The invention of geometry and its use is limited not only for the practical purpose of creating law and order on earth, it is essential for the fulfillment of psychological requirements of human beings. Ordered mathematical information generates positive emotional responses. Our attitude towards geometry is derived from our attitude of acceptance of the geometrical forms inherent in Nature. The proportions used in architecture were supposedly existed in the very nature of the universe of which Human

Being is an essential part and therefore by the application of these proportions in his environment, man participated in the harmony of cosmos.

The practice of geometry imparts rationality, compactness of the grouping of spaces and structural integrity necessary in architectural design. The size and arrangement of structural elements were fixed according to the overall geometrical scheme. The geometry of the circulation space unfolds the formal qualities of the built environment around it. Consequently, the arrangement and configuration of use-spaces and the pattern of movement together generate the geometry of the building. All the greatest buildings of the past successfully integrated variety of its subdivisions cohesively into hierarchy of inter connected scales thereby determining their overall volumetric geometry.

The approach and appreciation towards beauty depended partly on the way various civilizations created their respective world-view and attached symbolic meanings to architectural geometry thereby contextualizing its character which otherwise is universal in nature.

Primary geometrical shapes which are strongly perceptible and measurable are used in the architecture of exceptional importance. Apart form satisfying psychological and philosophical demands these shapes do procure seismic safety essential to the built form.

Geometry brings visual coherence corresponding to Vitruvian 'symmetry' which results because to collective relationship of parts due to balanced relationship of their size, number, disposition and order.

Therefore the importance of geometry lies not only in conceiving architecture analytically; it also manifests intangible principles through tangible form thereby bringing into play the intuitive faculties of both the designer and the user.

8.1.2. Geometry as a Constituent Fact in Architecture

As mentioned by Giedion (1956) [32], constituent facts reappear as and when they are suppressed. Their recurrence, all together produces a new tradition. We know that the geometrical principles which were applied from the Neolithic period to Renaissance were abandoned in seventeen century onwards when beauty was considered to be a construction mind and laid in the eye of the beholder with no relation to these principles. The recurrence of these principles in late nineteenth and twentieth century affirms their permanence in art and architecture. The application of same geometrical principles through several ages transcending place, culture and time has firmly established them as the fundamental constituent fact of architecture.

These principles always implicit in the creation of architecture and expressed so explicitly, impregnated with diversified meanings, in varied historical styles within which architecture is generally categorized, have thus regarded architecture as an independent organism least affected by space and time, though we all know that architecture by its very nature is inseparable form life as a whole. Architecture is therefore embellished with a universal outlook by geometry.

The recurrence of these geometrical principles through different ages over the passage of time in all types of buildings has confirmed the functional adaptability and flexibility inherent in them in fulfilling man's physical requirements so varied in function.

The knowledge of the past and feeling of what is coming in future is necessary for meaningful planning, the application of these geometrical principles provide us with a continuous tradition making past part of the present and future.

8.1.3. Geometry as Design Idea

The use of same geometrical principles as the fundamental design ideas in the past as well as in the present establishes them as the generic ideas of any design solution from which innumerable patterns can be developed as per the requirements in space and time. It also provides us with the opportunity for better understanding of history and for healthy interaction between history and design so essential for meaningful continuity thereby establishing a permanent design vocabulary for analyzing and designing architecture. It thus imparts more dynamism to the study of history of architecture as it is interesting to analyze how these limited timeless principles entered into the matrix of contextuality in different periods creating limitless enriching architecture. Geometry thus provides a logical basis in the development of design essential for the rational approach towards form rather than leaving it purely at the personal choice and fancy of the designer.

8.1.4. Geometry and Aesthetics in Architecture

It is generally the aesthetic criterion that determines the greatness of a building. The study of beauty as a quality lies is in the realm of aesthetics. There have been two major theories of Aesthetics:

One deals with autonomy of forms where beauty is the primary result of special formal relationship. It establishes the supremacy of proportions in design and regards the secret of architectural beauty in specific mathematical relations. This concept is based in an ideal absolute towards which the beauty of form converges. This theory is thus in line with Plato's ideas of eternal beauty. Another thinking about aesthetic theory is based on the concept that beauty in architecture depends on what it expresses. The intensity and quality of expressiveness determines the beauty. The use of primary and regular geometrical forms predominantly contributes towards this end; but in both the cases beauty lies in the artifact itself.

The other theory was developed in seventeenth and eighteenth centuries when science of psychology was created. The sense of beauty was a psychological fact determined by the reaction from the object rather than in object itself.

The research has shown that the former theory of aesthetics based on geometry as a mathematical product with its world of numbers and proportions having their inherent structures of interdependent 'growing' figurations establish its close association with Nature.

Many researchers have established through the study of these proportions in Nature that the imaginative application of these geometrical systems assure necessary harmony and variety in composition. It therefore provides scientific base to the theory of aesthetics which already existed from ancient period.

8.1.5. Geometry and Creativity in Architecture

Creativity is the tendency to generate or recognize ideas, alternatives or possibilities for solving problems, communicating with others, and for entertaining ourselves and others as well. For this the need is to see things in new ways or from different perspective.

According to Pasteur's famous dictum "Chance favors the prepared mind" which means that the element of chance in creativity is most likely to occur in the mind which has grasped the existing knowledge and skills relevant to be creative. Only then one is able to give original contribution and even in a position to recognize some thing worthwhile and original. Creativity therefore is related to originality and novelty, but this novelty must have some value relative to what already exists as being needed. Creative outcomes are generally the novel recombination of the existing elements. Probability of creativity thus depends upon the sufficient command of the already existing skills and knowledge.

In this sense, creativity in architecture depends upon the understanding of the constituent facts of architecture and by observing and analyzing the phenomena of Nature. It is interesting to see how these geometrical systems while operating within their limits have created limitless patterns in the ageless and harmonious works of architecture. Mastering skillfully the art of generating varied forms through these limited systems is the key to create harmonious architecture. The skillful use of these systems by the designers at the city level will certainly result in harmonious and rich urban form; so appreciated a phenomena in the historical cities which we know is due to the application of the limited geometry.

Le- Corbusier, strongest pillar of modernism responsible for defining by creating modern art and architecture designed his buildings based on his understanding of the inherent geometry of the historical buildings. For the standardization of sizes of building components, he created 'Modulor' based on the dimensions of human body and the concept of golden section thereby utilizing these already known proportions in contemporaneous manner.

Similarly, one of the leading architects of contemporary scenario Peter Eisenman, has first understood and reinterpreted the architecture of the past and then created his vocabulary of architecture. His buildings apparently different from the historical ones, challenge their age-old concepts and search for new domains in architecture but are the results of the application of same geometry.

The ultimate goal of creativity is to generate valuable novelty by transcending conventions which can be achieved by mastering the existing knowledge and skills.

8.2. CONCLUSIONS BASED ON STATISTICAL RESULTS

8.2.1. Mathematical Proportions

(i) These proportions are found to be significantly incorporated in buildings having centralized forms with corresponding spaces along with secondary units of spaces placed adjacent to them creating a visible hierarchy or in buildings with series of forms and related spaces sequentially arranged in row/s forming overall linear configuration. These configurations have strongly been imbued in the flavors of their prevalent styles. While the centrally dominated organizations are employed to embody sacred or honorific places, the linear configurations on the other hand are more flexible in nature responding easily to the features of the site. The best possible results occur in the meaningful combinations of these two types of forms and respective spatial organizations.

(ii) Such buildings are approached either from the oblique direction to enhance the visual experience or from the front side with approach running perpendicular to the main façade. The combinations of the front and oblique approach are found to be best suitable to enhance the experiential quality of the building.

(iii) The interior spaces are decisively integrated in the circulation network with movement pattern passing through the spaces finally terminating in a main space. This relationship of interior spaces with the movement pattern is commonly observed in sacred or honorific buildings. The configuration of the path is strongly orthogonal and axial in nature, thereby imparting axiality as a visual ordering device in such buildings. The axial path generally acquires symbolic meaning. In the case of linear organizations, the spaces are placed adjacent to each other on both sides of the movement path. The axiality is reinforced when the overall form is a combination of linear and centralized configurations.

(iv) The load in these buildings is found to be transmitted through right angled systems rigid or non-rigid in nature using RCC framed structure in case of rigid ones and post and lintel system in non-rigid ones and/or through spherical system with the help of domical or shell forms. In some cases, partial load is transmitted diagonally through truss/es in combination with these systems. Structural materials durable in strength are employed in such buildings.

(v) Such buildings are resistant to earthquake by being light weight through the selective, economic and articulative use of structural materials and by the proper integration of structural and non-structural elements.

(vi) The buildings where these proportions have been incorporated have employed relative and/or preferred measures for the interrelationship of different parts with each other and simultaneously with the whole structure.

(vii) Mathematical proportions are incorporated in structures which are either open to sky or receive natural light predominately through walls.

8.2.2. Golden Proportions

(i) Though different cultures have regarded it with varied symbolism, golden proportions have been significantly applied in the making of aesthetically meaningful architecture. Its use increased manifold after Adolf Zeising re-established it importance in 1835. The very implicitness of this system in the natural phenomena so beautiful and varied has provided architects with sufficient reasons to incorporate them in their buildings.

(ii) The overall organization is generally a result of addition of repetitive forms with corresponding spaces placed adjacent to each other. This 'additive' quality of different parts sharing common visual feature creates unity in the composition along with the desired richness which results from the transformation of various parts determining strong visual order. Such order is predominately found in nature and keeps on inviting various researchers to explore its principles of beauty. The repetitive arrangement of common form/s adds flexibility in use and also provides boost to the phenomena of standardization in architecture without creating the danger of monotony.

(iii) The buildings where golden proportions have been applied to exhibit strong visual weight by the playful use of massing, emphasized corners through different means and by textured surfaces of enclosing forms.

(iv) The load is transferred through right angled and/or spherical system including domes and vaults. In older buildings, stone was predominantly used as a structural material where this system is used.

(v) The modern buildings with this system show resistance to earthquake by being light weight and through the effective integration of structural and non-structural parts.

(vi) Golden proportions are found to have been applied predominately in either open to sky structures or in the building receiving natural light through roof directly or indirectly.

8.2.3. Geometrical Proportions

(i) This system has been used most extensively in architecture through out the history. Because of the implicit symbolic and visual references attached to the geometrical forms simultaneously fulfilling the functional criteria efficiently, it has been employed forcefully in buildings of religious, philosophical or spiritual importance in all the diverse cultures.

(ii) This geometrical system is significantly found in buildings with centralized spatial organization and/or clustered organizations where secondary spaces are placed adjacent to main space for symbolic reasons or repetitive spaces are fitted with each other by physical proximity to efficiently fulfill the functional requirements. Such organizations are acceptable to growth and change thereby imparting flexibility without rapidly affecting the character of the building. The best results are achieved through the meaningful integration of symbolic, visual and functional requirements along with necessary flexibility. Symmetry is found to be the strong visual ordering device in such buildings.

(iii) These buildings are approached through front facade with approach way perpendicular to this facade while the significant movement pattern inside the building is found to be radial in configuration with linear paths extending from or terminating at a central point.

(iv) Since these buildings are flexible in nature the movement paths are integrated with interior spaces generating variety of patterns creating diverse experiences to respect the psychological needs of man apart from fulfilling functional criteria efficiently. The path passes through the spaces, by the space and is found to terminate in an important space of symbolic, visual or functional importance.

(v) The buildings incorporating geometrical proportions are found to be embellished with interesting optical patterns on the outer facades thereby adding visual weight and creating richness and variety in the form.

(vi) Spherical transmission system in terms of arches and domes predominately transfer the gravity loads.

(vii) Buildings with this geometry are significantly resistant to earthquake because of the symmetrical arrangement of different units, proper isolation of the structural and non-structural parts. The ratio between longer and shorter sides of such buildings is found to lie between 1:1 to 1:2, which is considered safe from earthquake point of view.

(viii) Such buildings were constructed with concrete and other locally available materials in earlier periods, while in twentieth century RCC is found to be commonly used.

(ix) Relative measures have been used in such buildings for creating order among different parts with each other and simultaneously with the whole structure.

(x) These buildings are found to receive natural light indirectly through roof.

8.2.4. Regulating Lines

(i) Regulating lines are found to be significant in buildings of religious, philosophical or spiritual importance mostly concentrated in eastern civilizations. The application of this system was favored for aesthetic criteria for imparting harmony in compositions. It does not possess any specific symbolic value.

(ii) This system is significantly associated with centralized and/or linear forms. The visual interest from inside and from outside form, in some cases, is generated through the use of interlocking spaces.

(iii) The interior spaces here allow the movement path to pass through them which finally terminates in an important space, thereby instrumental in the creation of symbolism associated with those buildings.

(iv) The hierarchical co-operation in terms of interrelationship among different scales is found to be good in some cases, average in others or may be a combination of good and average in the same building. On the whole, the building strongly exhibits human scale.

(v) The earlier buildings organized according to regulating lines were generally compressive structures with non rigid right angled load transmission, with the use of RCC and steel as the chief materials, such buildings were made as rigid right angled structures.

(vi) The ratio between longer to shorter side of these buildings is found to lie between 1:1 to 1:2, thereby exhibiting safety from earthquake.

(vii) Such buildings are either open to sky structures or receive natural light directly through walls.

8.2.5. Module-Based Proportions

(i) The modules are determined according to the prevalent technology, resources and style of the period thereby making the building deeply rooted in its time and place. In contemporary period, it is one of the most preferred systems as it provides boost to the concept of standardization and prefabrication in building industry.

(ii) These proportions are found to be significantly associated with linear form which consists of repetitive units placed in sequence thereby ensuring the flexibility of growth and change without much affect on the overall form, simultaneously imparting unity in the organization.

(iii) Buildings with these proportions are found to possess linear configuration of the movement path inside them. Different units are linked with each other through the movement path passing by them.

(iv) Buildings possessing these proportions have strong visual weight determined by the textured surfaces of the enclosing forms.

(v) Since this system is based on the repetition of different modules, the overall form and different parts exhibits human scale in its organization.

(vi) Spherical load transmission system in the form of arches is found to exist in such buildings. In earlier examples, stone was the chief structural material used in these buildings.

(vii) The structural parts are either properly integrated with non-structural elements or are effectively isolated from them to ensure safety from earthquake.

(viii) Such buildings found to have employed absolute and/or preferred measures for aesthetical, functional and economic reasons.

(ix) The buildings using these proportions are found to receive natural light directly through walls or they are open to sky structures.

8.2.6. Preferred Dimensions

(i) This system is found to be significant with all types of symbolic and visual references. It simultaneously ensures the functional efficiency of buildings where it is used being based on the proportions of human body.

(ii) The kinds of organizations that are found to be profoundly associated with this system are additive as well as centralized ones created by the placement of centrally dominantly space surrounded by secondary spaces. The dominant and surrounding spaces are interlocked with each other through diverse ways determining unity and fusion in the interior of the building.

(iii) The buildings based on this system have strong visual weight through articulative interlocking of masses, optical patterns creates on the facades and textured surfaces of the forms. The corners are however smooth or non much emphasized.

(iv) Being based on the proportions of the human body, the buildings with this system generates human scale in relation to spaces, form organization and juxtaposition of different parts inside and outside as well.

(v) The loads are transferred through any one or combination of many systems like rigid right angled frame or through domes and/or shell or by diagonal system. RCC is the most predominant structural material.

(vi) Such buildings being light weight ensure safety from earthquake.

(vii) The natural light in these buildings is received in indirect manner through the walls.

8.3. CONCLUDING REMARKS

Geometry, which rests on the handful of simplest and primitive rules has been wrought by imagination and logic by the designers throughout the ages in all parts creating order universal in nature imbued in the regional diversities of the world. The common language of these geometrical systems testifies the existence of deep-rooted unity transcending all the boundaries of space and time thus establishing the objective and universal standards for the creation of meaningful forms. These provide readymade intellectual structure over which necessary articulations can be done to impart the colours of contemporaneity and vision suitable to the times.

These geometrical systems limited in number are powerful enough to act as a force behind limitless creation. They simply demand an integrated approach incorporating all the necessary parameters right from the beginning of the design stage for their systematic and successful application in architecture. This research is a step forward towards the formation of the logical structure integrating necessary parameters for the application of these geometrical rules.

8.4. LIMITATIONS OF THE RESEARCH

1. The analysis and conclusions derived were based on the investigation of forty buildings. However better results can be obtained out of larger Data Base.
2. The research work was purely based on the information extracted from literature and not on empirical studies. Therefore, at some places necessary assumptions had to be made to accomplish the task.
3. Dichotomous data was generated for analysis in respect of dependent and independent variables in the form of '0' and '1' in the two-dimensional array. However, the accuracy of results can be increased by increasing the range of values and assigning them to each variable based on its actual amount of contribution in the making of architecture.
4. The research did not seek in detail the interrelationship of geometry with the functional efficiency of the buildings.

8.5. SUGGESTIONS FOR FURTHER RESEARCH

The relationship of geometrical systems especially with the functional aspect can be analyzed in detail by integrating empirical studies with theory in order to make architecture more meaningful.

This research, which is universal in nature, can be further carried out by interrelating these geometrical systems with other important aspects like socio-cultural conventions and political influences of an area which impart, richness, variety and regionalism to architecture. Some of the geometrical systems have been found to provide a suitable base for standardization and mechanization of building components. Intensive research in the area relating geometry with prefabrication can be carried out for making construction work speedy and cost-effective simultaneously imparting necessary variety in buildings.

This work concentrated upon individual buildings. It can be further extended to create urban responsive architecture by establishing the relation of the geometrical systems with surrounding built form thereby resulting in harmonious urbanism.

It is a truism that the profession of architecture cannot be completely formulated into few mathematical interpretations owing to the vast qualitative, intangible elements, falling into the realm of feeling, integrated with quantitative aspects which collectively result in determining the domain of human control. However, this research is a step towards making a frame work of taking certain decisions regarding architectural form, objectively in a rational, logical and holistic way.

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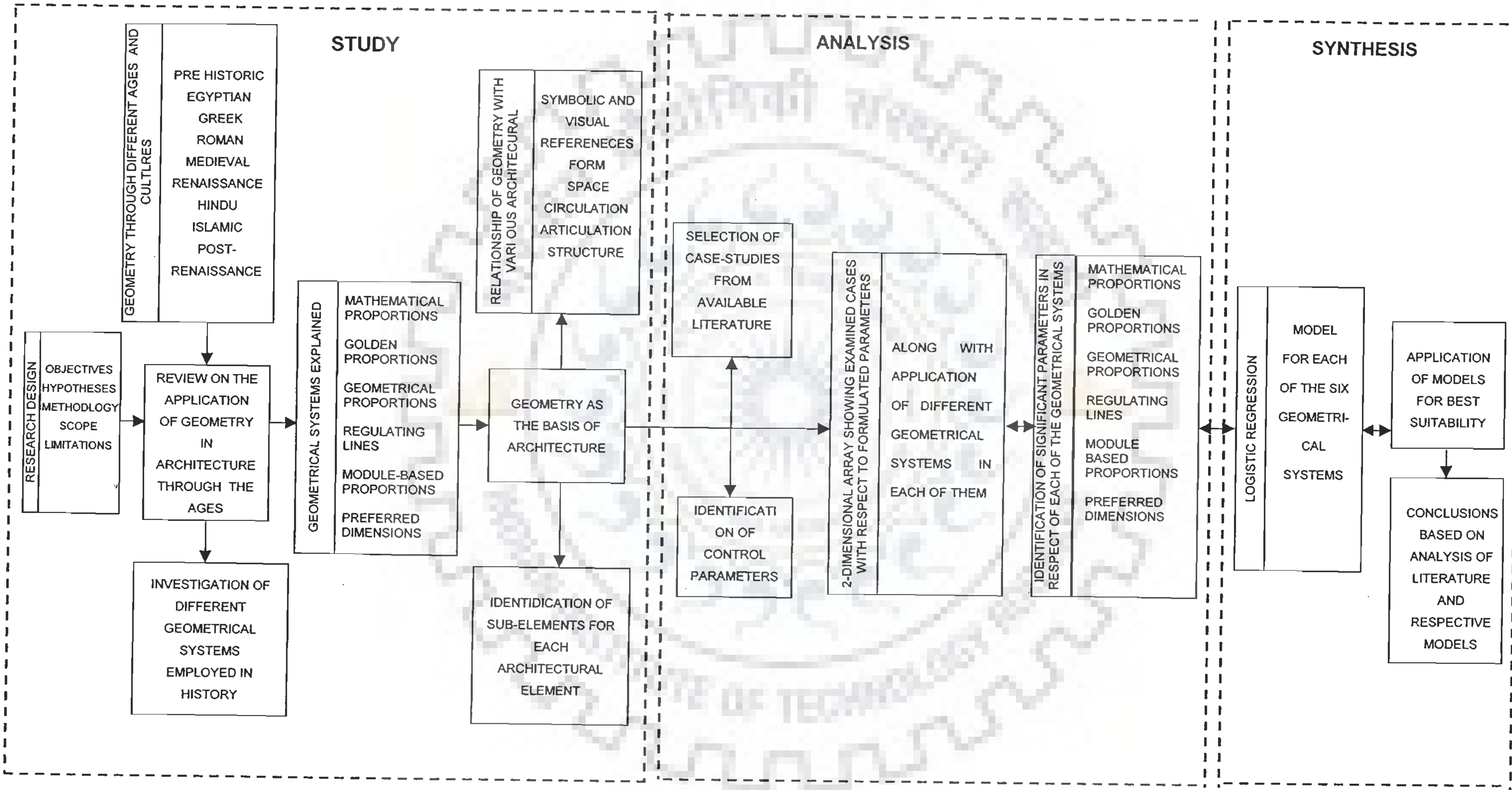

APPENDIX – I
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