Structural Form in History and the Construction of Complex Forms

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ABSTRACT: Form is one of the inherent common interests of architects and engineers. A study of form in the design and construction of buildings has shown that there is furthermore a link between theory and practice where the built architectural form, especially the complex form is concerned. This link relates primarily to the communication and the execution of a design into the final built form.
A brief summary first shows the impact of scientific discoveries in the field of structural engineering on the design of shapes in architectural history. The use of complex forms is not only influenced by the scientific and technical knowledge but also by social circumstances. Although first designs breaking out of the simple geometrical pattern can be found since 1700, the complex designs only managed to establish themselves around 1900. Different methods of translating complex shapes from the sketch to the finished building are demonstrated with three significant examples from the era before the application of computer technology.

INTRODUCTION

The concept of form is a prevalent theme in architectural history. The increase of non-orthogonal, complex shapes in architecture being designed and built in recent years motivated the research into the history of architectural form, how it was influenced by theoretical knowledge, and how complex shapes were accomplished without the help of modern digital tools.
Hermann Finsterlin, a German artist, poet, and architect, divides architecture into three phases: the era of the coordinate with primary form elements in a proportional grid, the era of geometry with a splitting of elements and the organic era where hybrid form elements are merged into one another (Borsi 1968, p 46). More specifically, forms have been divided into three families: geometrical forms, physical forms and free forms (Burkhardt 1986, p. 36). Here, the distinction is made between simple geometric and complex forms, the latter of which can embrace the physical as well as the initially undefined, free forms.
The implementation of elementary geometrical forms in history has been facilitated through their regularity. Straight, orthogonal lines, right angles, sections of circles, or ellipses are as readily drawn on paper as they are constructed on site. The regularity of the shape also makes a reduction of the structure to two-dimensional systems possible, which simplifies the structural design. The communication and the design of a shape with many variables, however, are much more complex and demand an elaborate process of planning and execution.

THE DEVELOPMENT OF FORMS IN HISTORY

The architectural shape shows typical principles in each time period, which are dominated by different aspects, ranging from the laws of physics to social factors. The scientific knowledge, i.e. basic knowledge in physics, mathematics or material sciences, but also technical possibilities like available tools and materials had an influence on the used shapes at all times. Even if first designs of free forms - and some of the houses designed by Finsterlin can be counted among those - were not controlled by this knowledge, the verification of these can certainly be ascribed to the existing technical and structural expertise.

Forms until the Nineteenth Century

Simple, geometrical forms dominate architecture up to today. This situation is contrary, incidentally, to the nautical, automobile or aeroplane industries, even though the building sector has always been influenced by technical innovations in these fields. Straight lines, circles or the platonic polyhedrons had a symbolic significance and were therefore important from a formal point of view. Apart from the theoretical aspects, the translation of the design into a built edifice involved the use of straight lines or sections of circles as they were easy to construct. The tools for measuring and marking like string, plumb line, angle, compass, or template were of immense importance and influence on the built shape (Otto 1989, p. 203) For large building projects like the gothic cathedrals, sections of arches could be efficiently prefabricated, if the arches had a constant radius, and were interchangeable, within the arch or with another building.
Apart from the theoretical aspiration of accomplishing an ideal geometry, requirements of practicability and efficiency in traditional craftsmanship brought about shapes that were not necessarily geometrically simple but were rather created by a process of empirical form creation over generations (Graefe 1986, p. 50). These shapes were conceived step by step to be able to assess load bearing principles of materials and structural systems and also of the built form itself. From a structural point of view, this knowledge and ability of the craftsmen led to a continuous development of constructions. The heavy masonry buildings of the early Middle Ages gave way to increasingly slender and more efficient structures finding its first culmination in gothic architecture, where walls were substituted by columns so that large openings for windows were possible. The stability of these buildings was ensured by slender abutments. Thus, even if the use of simple geometrical shapes was still predominant, an important step was taken to dissolve heavy, massive building types into slender frames. As Rowland Mainstone comments: „Structure, construction, and visually-expressive form were (…) virtually indistinguishable." (Mainstone 1975, p. 26).

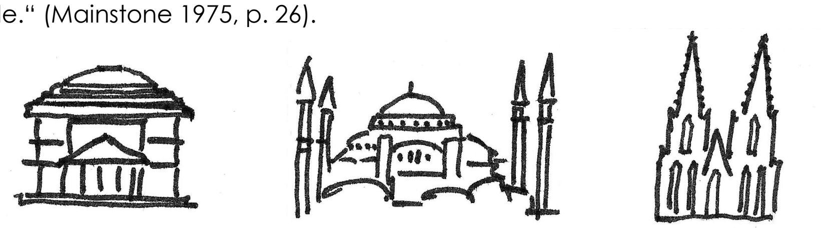

Figure 1: Examples for architecture based on basic geometric forms: The Pantheon in Rome (around 125 B.C.), Hagia Sophia (563 A.D.) and the Cologne Cathedral (started 1322); (H. Rogers)

To develop the structural systems further, scientific knowledge of forces and resistances was necessary. In the 17th century, in his book „Discorsi e Dimostrazioni matematiche" (1634), Galileo Galilei (1564-1642) concerned himself with form in structures. He used real building elements as a basis to find theoretical models. For example, he designed the shape of a cantilever with a point load, so that over its length every section was used to its full capacity. Also, he compared the load bearing capacity of beams with full or hollow sections (Kurrer 2003). This represents an early research into the efficiency and the optimisation of structural elements in direct relation to their shape, which are still relevant today.
At the end of the 17th century, Robert Hooke (1635-1703) formulated the law of the arch formed as an inverted hanging chain – „ut pendet continuum flexile sic stabit inversum rigidum" (citation after Graefe, 1986, 53). Apparently, he was able to convince the architect Sir Christopher Wren (1632-1723) of the advantages of using this form. Wren then applied this knowledge to build the St. Paul's Cathedral in London (1674-1711). Even if the outer and inner domes of the cathedral were still strictly geometrical shapes, this first known conscious use of the inverted catenary shape in a building was another step towards building complex shapes.
As an architectural shape, the shape of a building following the thrust line was generally not accepted for a long time and only in the beginning of the 20th century the potential of these shapes was appreciated. This appreciation was supported by the awareness, that a structural form that is generated allowing for the flow of forces will usually be more efficient, an insight which was also applied in the Graphical Analysis by Karl Culmann (1821-1881) by the end of the 19th century. Culmann developed the Graphic Analysis for the rationalisation of the engineering design, but also to be used as a tool to combine structural and constructive design – thereby having an impact on the aesthetics of the structure.

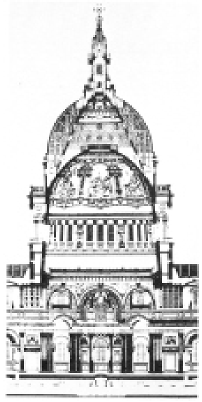

Figure 2: Section of St. Paul's Cathedral by Sir Christopher Wren, 1674-1711; (Otto 1985, p. 47)

With the industrialisation at the end of the nineteenth century, simple geometrical shapes for the structural elements gained in importance as they were easily made in large numbers on the production lines. The no-frills aesthetics of industrial buildings in England resulted (Strike 1991), contrasting the heavy ornamentation of the historicising architectural fashion during that period. In spite of the very rational approach of industrial production, the modular structures of trusses allowed its own aesthetical language. Due to the large demand for iron and steel, an economical use of materials was necessary, leading to minimisation of sections and increasingly slender elements. With the help of the Graphic Analysis, the influence of a chosen form on the ensuing forces could be clearly demonstrated and thus led to the development of form to achieve efficient structures.
Gustave Eiffel (1832-1923) also made use of the Graphic Analysis to develop form and construction of his projects around the world. The tapering form of the 300 m high Eiffel Tower for example was generated by a graphic analysis of the occurring wind loads, showing the influence of the loading on the design (Burkhardt 1988, p. 156). A sketch from 1887 shows this design process.

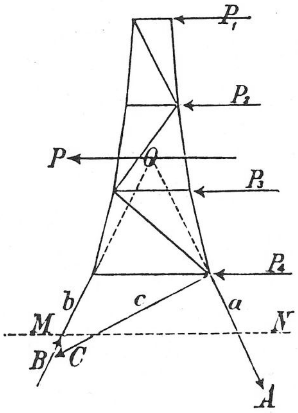

Figure 3: Horizontal loads and the resulting shape of the Eiffel Tower, 1887; (Burkhardt, 1988, p. 159)

With the Industrial Revolution, the development of the constructions had in turn repercussions on the structural research. The relatively simple model of a truss with pinned nodes was not sufficient to describe the usually riveted constructions. Nor was it possible to design structures like the Vierendeel truss, named after the Belgian engineer Arthur Vierendeel (1852-1940) with this method. The desire to be able to understand their load-bearing behaviour and the secondary stresses in stiff connections as well as to activate the residual capacities of structures led to new research into indeterminate structures. Heinrich Müller-Breslau (1851-1925) devised a theory on indeterminate, linear-elastic frameworks and thus established another foundation of modern structural design.
These theoretical findings as well as the capacity of the new materials iron, steel, and concrete led to the application of more and more slender structures and opened up new possibilities for the development of form in architecture, even though the basis for all but a few designs was the pure geometrical form. However, the theoretical knowledge about materials, flow of forces, and indeterminate structures laid the foundation for the progress of form development in the twentieth century.

Forms in the Twentieth Century

The beginning of the twentieth century marked a turn in arts and architecture. The overuse of ornament and embellishment in an architecture glorifying the past led to a new use of geometrical forms. Under the principles of „Form follows Function" by Louis Sullivan (1856-1924) or „Less is More" by Ludwig Mies van der Rohe (1886-1969), designs of buildings with a very linear, rational geometry were evolving. At the same time, however, a number of architects abandoned the orthogonal grid motivated by the thought that natural, flowing forms were beneficial for the well-being of man. To name a few, Hugo Häring (1882-1958), Erich Mendelsohn (1887-1953), or Rudolf Steiner (1861-1925) planned projects that showed forms other than straight lines. The many free flowing contours in the designs of Herrmann Finsterlin (1887-1973) were especially resourceful, but unfortunately never built.

Figure 4: Hermann Finsterlin`s Design for "The Red House" from 1922; (Borsi 1968, p. 77)

Another designer of flowing forms was the Catalan Antoni Gaudí (1852-1926). At the beginning of the 20th century, he built several buildings in Barcelona out of masonry, the shape of which was based on the thrust line theory. For the chapel of the Colony Güell he made a model out of threads, hanging small weights off it to simulate the dead load of the structure. This shape was then mirrored to create a masonry structure which was in compression under its self weight. But Gaudí's creativity also included geometrical shapes as is demonstrated by the roof of the school for the Sagrada Familia, made up of conoids. Gaudí used the structure as a load-bearing as well as an aesthetic element.

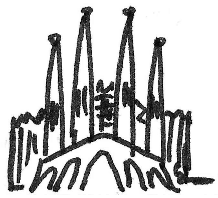

Figure 5: Gaudí's Sagrada Familia Cathedral, started 1882; (H. Rogers)

The development of reinforced concrete showed a similar use of the material as structural and visual at once. The Swiss engineer Robert Maillart (1872-1940) developed a flat slab with drop panels and many bridge designs allowing for the flow of forces in the new, monolithic material which resulted in a very specific formal aesthetic. Also the emerging concrete shells utilised the potential of material and shape which was not least due to the necessity to use all material efficiently. The shells, however, were mostly based on geometrical shapes like spheres or ruled surfaces. Examples are the buildings by Eduardo Torroja (1899-1961) from the 1930s and the numerous variations of hyperpolic paraboloids by Felix Candela (1910-1997) in the 50s and 60s.
This simplified the necessary static calculations and also the building process. Where Gaudí had to conduct the building of his complex forms with templates, the setting out of the spheres and ruled surfaces on site was

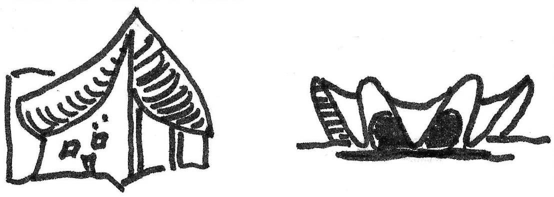

Figure 6: Corbusier used conoid-shaped concrete shells for the roof of Ronchamp (1954), and Candela's design for the Xochimilco Restaurant (1958) was based on the hyperbolic paraboloid; (H. Rogers)

significantly less elaborate. The forms of Heinz Islers (*1926) shells, however, which he builds up until today, were mostly developed with physical experiments, by inversion of hanging cloths or inflating rubber membranes. These were also mathematically complex and Isler, like Gaudi, had to communicate the intended shape directly on site.
With the progress of theoretical knowledge and new methods of static design calculations, for example the theory of shells, the second order theory, or the iterative calculation of section loads in highly indeterminatestructures, a systematization of calculations was necessary and led to the use of calculation tables and matrices. This in turn required a growing abstraction of the structure on paper which didn't lend itself to the thinking in alternatives but rather led to the mere mathematical solving of given problems. After 1950 the continuing abstraction and thus specialization of structural engineers resulted in the possibility of using machines to solve the increasingly complex calculations . The first computer was invented by the structural engineer Konrad Zuse (1910-1995). By adapting the finite element systems from the aerospace industry the computer facilitated the calculation of complex structures by automisation of the calculation process and in addition made the understanding of difficult geometries and solutions easier by the graphic visualisation of the input data and the results.

In the second half of the twentieth century, the buildings grew higher and the bridges spanned further due to the possibilities of exact calculations and the ensuing efficiency of structures. The invention of prestressing, the high performance steels and concretes as well as composite constructions or materials supported this development. It was also the basis of the cable and membrane structures which evolved since the 1960s, principally at the Institute for Light Surface Structures in Stuttgart under the inspired leadership of Frei Otto, with the desire to build very light and efficient structures, creating a new aesthetic in architecture.
With the computer, the architectural design today is only marginally dependent on the rationalisation of the calculation which was necessary before the use of very powerful computing programmes to prove the structural integrity of buildings. Since the end of the twentieth century, an architecture of undefined forms is spreading, which is not based on simple geometrical shapes nor physical forms developed for their efficiency allowing for the flow of forces. These initially undefined geometries are referred to as free forms and are generally considered to have appeared with the use of the finite elements and the computers. The description of the free forms and the determination of their geometry are extremely difficult with traditional means. With the use of the computer, their communication, visualisation, and computation is immensely facilitated. Many buildings in history illustrate, however, that very complex forms have been built "by hand" for some time.
The following examples have been chosen to give an indication of the possibilities and the different methods with which complex design geometries were realised. The three projects stem from a time period between 1880 and 1980.

FROM CONCEPT TO BUILDING

Scale Models: The Statue of Liberty 1875-1886

The Statue of Liberty was constructed in 1886 in New York City, U.S.A.. Although not referred to as a free form, as its shape is a representation of a human figure with a torch, its surface is nevertheless a mathematically complex shape which had to be communicated from design to construction. Architect of the Statue of Liberty was the sculptor Frédéric Auguste Bartholdi (1834-1904), Gustave Eiffel (1832-1923) was responsible for engineering its structure.

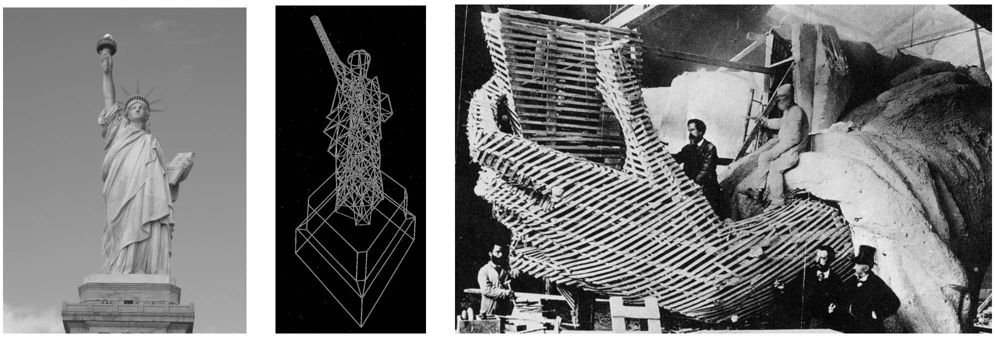

Figure 7: The Statue of Liberty from 1886; (P. Rogers, Hawkes pp. 27, 26)

The structure of the Statue of Liberty consists of a pylon as a main element, which is extended by a truss for the lifted arm. The pylon consists of four braced columns and carries a secondary structure which approximates the final shape of the figure. The surface is made of 2 mm thick copper plates, which are fastened to the secondary structure by means of bent flat irons, flexible enough to take differential movements between the two layers. This concept of the main structure resulted in a simple truss solution which could be calculated and produced easily with the skills available during that time. The final shape of the edifice was evolved through a series of models which increased in size – this process was initially purely sculptural. Finally, models to a scale of 1:3 were prepared, out of which craftsmen took distinct parts to transfer them into 1:1 plaster models.
Afterwards, moulds made out of timber laths were constructed around the plaster models. The copper plates were beaten into those moulds to receive their final shape and then erected provisionally in the back yard of the factory in Paris before being sent to their intended destination in New York.

Hand-applied finishes: The Einstein Tower 1920

The 16 m high Einstein Tower was built in 1920-21 in Potsdam, Germany. In the concept stage, the tower was envisaged by Erich Mendelsohn (1887-1953) as a concrete building. First sketches were showing a form that was generated from the functional requirements of a building for astrophysical research, housing a large telescope. Gradually Mendelsohn revised the shape of his design to result in the flowing contours we see today. Every stage of the design was verified by accompanying models.

Figure 8: The Einstein Tower from 1920; (H. Rogers)

Mendelsohn perceived the relatively new material of reinforced concrete as particularly suitable to express the dynamic character of the tower. After consultation with the contractor, the company Bolle, brick was found to be considerably cheaper, so that the final design was using mostly masonry. Only a few parts like the entrance area and the roof parapet were carried out in lightly reinforced concrete.
The floors are constructed in brick with steel reinforcement spanning between steel beams. Steel beams are also used for lintels and as transfer structures where needed, as it was customary during that time. The structure was built according to plans, approximating the planned shape. Afterwards, a layer of plaster was applied in varying thickness to accomplish the final form. This construction method bore the disadvantage of varying thicknesses in structural materials and plaster as well as a change of materials from masonry to concrete, resulting in continuous significant cracking of the building which has to be repaired time and again.

Simplifying Geometry: The Philharmonic Hall in Berlin

The Philharmonic Hall in Berlin was designed by the architect Hans Scharoun (1893-1972) and built 1957-63 as a new venue for the Berlin Philharmonic Orchestra under the conductor Herbert von Karajan.

Figure 9: The Philharmonic Hall in Berlin from around 1960; (H. Rogers, Wisniewski 1993, p. 53)

Scharoun's underlying idea for the form of the hall was his observation that people spontaneously form circles around street musicians to listen. This thought was integrated into his design of a centred room, where the audience is grouped around the stage. The ceiling was to have a high point above the stage. As a dome was not acceptable for acoustic reasons, a pointed shape of the roof was chosen. The roof structure was initially envisaged as a tent-shaped reinforced concrete shell, but this plan was discarded because of the high complexity of the formwork. For reasons of noise control with expected air traffic over the hall, a double layered construction was necessary. The second, flexible layer would have had to be supported by the shell resulting in high horizontal loads on the supports.
Therefore, a fairly conventional structural system was chosen. After the design of a system of large steel trusses was also dismissed, five parallel beams made of prestressed concrete with varying height was chosen and implemented. With a span of up to 52 m they carry the two layers of slender in situ concrete slabs (Grupp 2006). These two structural slabs approximately follow the intended shape of the roof and are composed of folded and twisted surfaces. The formwork was constructed of straight girders between the main prestressed beams, thus forming ruled surfaces, but simplifying the setting out of the structure. The internal ceilings were then formed according to the intended geometry and suspended off the concrete structure (Wisniewski 1993, p. 97).
A structural model for the verification of the design calculations was not necessary for the roof due to the simple structural system of one-way spanning slabs on supporting beams. However, an acoustic model that was built at a scale of 1:9 was very valuable to the contractor to understand the intricate geometry of the hall, not easily determined with the use of plans and sections. When mistakes were made setting out the foundations, additional, very closely positioned sections of the roof were provided by the architect to detail his geometric requirements. Generally, reference points from Cartesian coordinates were used to set out the building.

CONCLUSION

Up to 1850, discoveries and scientific knowledge on material behaviour and the flow of forces in structures can not be considered influential for the choice of shape in architecture - apart from a few exceptions - when distinguishing between geometric, physical and free forms. Only afterwards, an independent and conscious development of form according to efficiency, i.e. the evolvement of physical forms, can be found. Although orthogonal grids dominate until today, a parallel movement in architecture to use flowing, curved contours established itself since the beginning of the twentieth century, which resulted on the one hand from the wish to break free from traditional architecture or to "build for human beings" and on the other hand from the need to use materials economically by building forms that carry loads efficiently.
The three given examples show different approaches to the implementation of complex designs on site using simple methods of communication from scale models to a simplification the geometry. All examples used multilayered constructions to be able to verify the required shape. The execution of complex designs requires the shape to be approximated by a function which can be communicated easily, thus often resulting in a similar, simple geometrical form. Alternatively, a direct transfer of the shape from a model can be used.

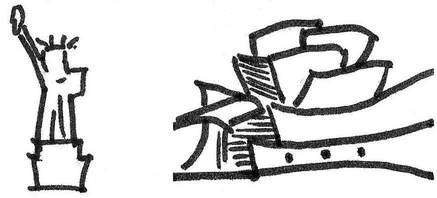

Figure 10: Similar structural concepts were used for the construction of the Statue of Liberty and of the Guggenheim Museum in Bilbao; (H. Rogers)

Although the engineers of the Statue of Liberty, the Einstein Tower, and the Berlin Philharmonic Hall were not able to fall back upon today's extremely potent tools of digital analyzing and digital communication, they were able to produce buildings with complex shapes. Interestingly, the methods of building used 100 years ago are still applied in the construction process of today. The truss solution with a secondary structure used by Eiffel for the Statue of Liberty, for example, was also employed for the Guggenheim Museum in Bilbao in 1999 (S.O.M. with F.O. Gehry). Here, too, the formed skin was attached to the secondary structure with flexible steel elements.

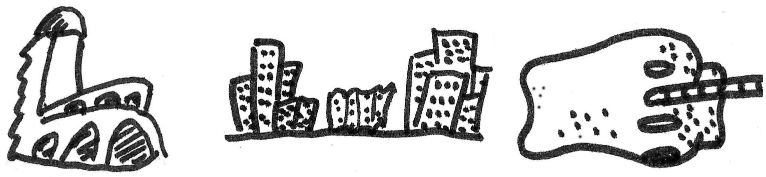

Figure 11: The Einstein Tower, the Neuer Zollhof in Düsseldorf and the Selfridges Department Store in Birmingham were all finished by a hand-applied outer layer; (H. Rogers)

The traditional masonry structure of the Einstein Tower with plaster of different thickness is comparable to the construction method used by Holzmann Technical Bureau for the Zollhof building C (Holzmann with F.O. Gehry, 1999) in Düsseldorf . Although high-tech methods were used to cut the complex shape of the steel beams which support the masonry façade, the final form of the building was accomplished by the outer layer, the plaster. Similarly, the façade of the Selfridges Store (Arup with Future Systems, 2003) was constructed with layers of concrete smoothed by hand to complete the final shape.

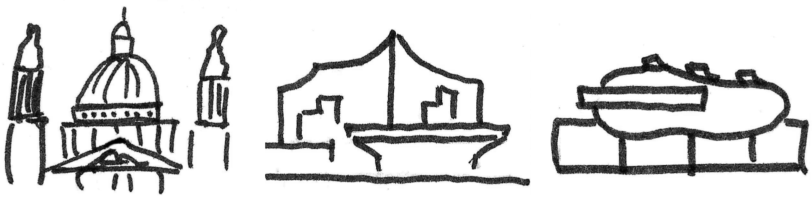

Figure 12: The load-bearing structures of the St. Paul's Cathedral, the Philharmonic Hall in Berlin and the Kunsthaus in Graz are clad to give the desired shapes; (H. Rogers)

Finally, the technique used for the Philharmonic Hall in Berlin, where the main structure is covered internally and externally by layers that will represent the designed shape, was not only used previously for the St. Paul's Cathedral around 1700, but also recently for the complex shape of the Kunsthaus in Graz (Bollinger & Grohmann with Peter Cook and Colin Fournier, 2003). On the outside, flat insulation panels and individually formed acrylic glass panes are fixed onto a welded polygonal steel frame. The inside is also covered.
In history as well as today, these methods were applied for complex mathematical or undefined forms, where the desired shape was not achieved by the structure itself. In this case, even with the huge data capacity of the computer, traditional methods of construction are still used.

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