

Analysis of Fractal Geometry in the Spatial and Structural Design of Ancient Chinese Architecture

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Abstract: Based on the theory of fractal geometry, this article explores the fractal characteristics of ancient Chinese architecture in terms of space and structure. The study reveals that using “jian” as the basic fractal unit, through iterative and self-similar mechanisms, a hierarchical spatial system from individual buildings, courtyard house, to settlements and cities has been formed. In terms of structure, components such as dougong (bracket set) and beam frameworks exhibit strict scale recursion and iterative logic. The research also reveals the fractal isomorphism between the “world” concept in traditional Chinese architecture and spatial organization, and further elaborates on the implications of fractal thinking for modern architectural design, evaluation, and historical environmental protection, providing a theoretical reference for the inheritance and innovation of Chinese architectural culture.

Keywords: Fractal geometry; Ancient Chinese architecture; Iteration; Self-similarity

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1. Introduction

About 300 BC, the Euclidean geometry founded by the ancient Greek mathematician Euclid has dominated people’s understanding, measurement, and calculation of shapes, guiding the construction of artificial objects with ideal shapes. This geometric principle is highly consistent with our daily life experiences, making it easier for people to accept. For example, what the Chinese ancestors believed as the round sky and square earth was explained by simple geometric shapes to interpret the natural form.

With the development of science and people’s continuous exploration of nature, using traditional Euclidean geometry has become difficult to precisely describe and analyze the irregular forms commonly found in many natural phenomena, such as clouds, mountains, and coastlines. To address these issues, French mathematician Benoit B. Mandelbrot first proposed the concept of “fractal” in 1973, gradually developing fractal geometry into a relatively complete mathematical theory, providing a new tool for humans to understand various complex forms in nature. The core concepts of fractal theory include “iteration” and “self-similarity”, meaning that local and

overall forms, structures, or functions have a certain degree of similarity and can be repeatedly iterated through relatively simple generation rules to form complex overall systems.

It is worth noting that although the fractal theory was formally proposed in the 1970s, its thinking mode has been deeply reflected in traditional architecture around the world. Especially in the ancient Chinese architectural system, from spatial organization to structural construction, it contains rich fractal ideas. This article will start from the perspective of fractal theory to systematically explore the fractal characteristics of ancient Chinese architecture in the two aspects of spatial composition and structural construction, and analyze its significance for modern architectural design.

2. Overview of fractal geometry and its application in architectural research

2.1. Basic principles of fractal geometry

The term “Fractal” was coined by Mandelbrot by combining the prefix “Fractus” (broken, fragmented) from Latin with the suffix “-Fractional” from English. This combined word is used to express the fundamental difference from Euclidean geometry. In simple terms, Euclidean geometry studies regular and smooth shapes such as lines, circles, and spheres, while fractal geometry studies the extremely irregular and non-smooth complex forms that are ubiquitous in nature.

Fractal geometry has the following basic characteristics: First, it has a fine structure, allowing the shape or object to contain very rich details at any small scale; second, it has self-similarity, meaning that the local and the whole have similarity in statistical or precise sense; third, it can usually be generated through simple iterative processes; fourth, its fractal dimension is greater than its topological dimension.

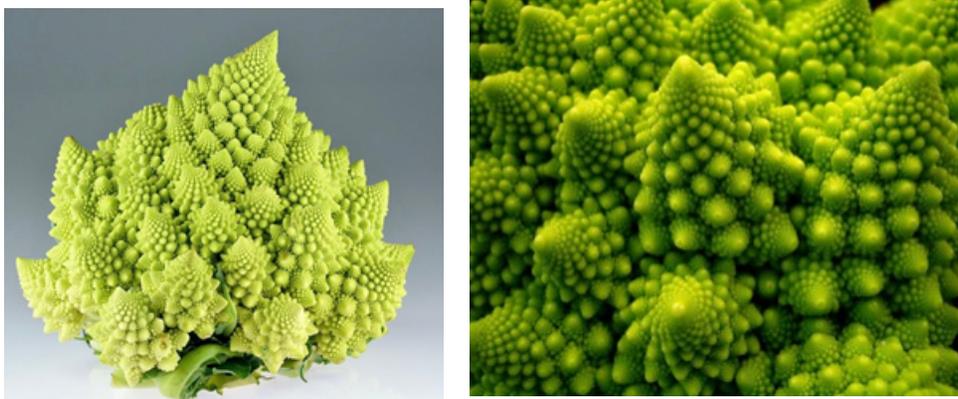


Figure 1. Details of roman cauliflower and cauliflower head.

In the theory of fractals, “iteration” is a core concept. Iteration refers to a mathematical process where a simple rule is repeatedly applied to generate a complex structure. For example, in nature, the Roman cauliflower (**Figure 1**) is composed of hundreds of florets arranged closely in an approximate Fibonacci sequence, and each floret has the same shape as the entire cauliflower, and each floret also has smaller florets arranged in the same way; when observing each small floret magnified, it will be found that the small florets are arranged in the same way by even smaller florets, and their shapes are also the same as those of the small florets and the entire cauliflower. Through iteration, the relationship between each local part and the whole reaches the self-similar state in fractal geometry. Another example is the famous Koch curve (also known as the snowflake curve, which was proposed by the Swedish mathematician Koch in 1904 as a research result), which is generated in the form

of a similar snowflake by continuously adding triangles in the middle of the straight line segments (**Figure 2**). This simple iterative rule eventually produces an infinitely complex and infinitely fine self-similar curve shape.

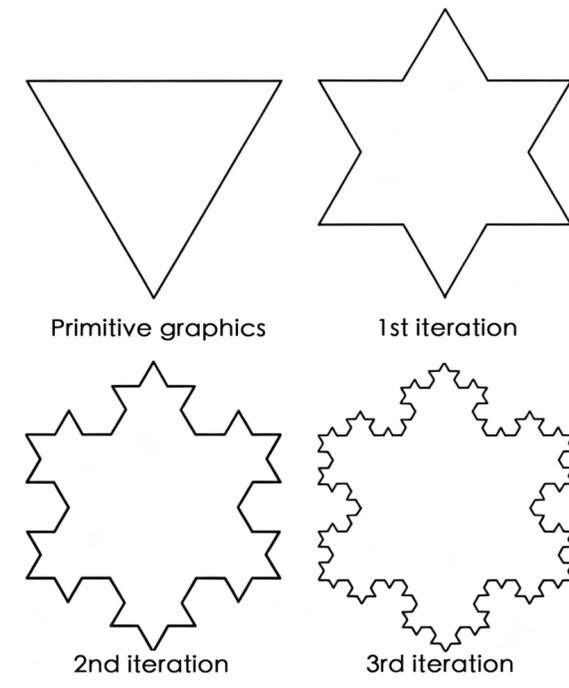


Figure 2. Graph of Koch Curve after 3 iterations.

2.2. Application development of fractal theory in architectural research

Since the 1990s, the application of fractal theory in the field of architecture has gradually emerged. Professor Carl Bovill, an architecture professor at the University of Maryland, first systematically introduced the fractal geometry theory into the field of architectural design and analysis in his book “Fractal Geometry in Architecture and Design”. He conducted graphical quantitative analysis of a large number of outstanding architectural works using the fractal geometry analysis method, discovering that architectural phenomena and architecture conform to fractal geometry laws, while traditional architecture often has a higher fractal dimension^[1]. The paper “Fractal Models in Architecture: A Case of Study” by Italian scholar Nicoletta Sala clarified the calculation method of architectural fractals. In his work “Informal”, British engineer Cecil Balmond proposed inspiring views on the application of fractal geometry in architectural design through structural diagrams^[2]. Yale University in the United States conducted a detailed analysis of traditional architecture in Africa, Europe, and India, and summarized the fractal structures therein^[3]. Professor Ron Eglash, an information science professor at the University of Michigan, used the iterative generation rule in fractal theory to analyze the images of African traditional architecture through a computer, confirming that traditional architecture has fractal properties and can be reconstructed using fractal iteration^[4].

In recent years, domestic scholars have also begun to pay attention to the application of fractal theory in the field of architecture. Professor Mao Yalong from South China University of Technology, in his paper “Self-similar Harmony: Explanation of Architectural Theory of Two Concepts and Three Features According to Fractal Theory” and his work “Architectural Design Research Based on Fractal Theory”, systematically

expounded the framework of fractal architectural theory and proposed that fractal thinking can provide new ideas and methods for modern architectural design.

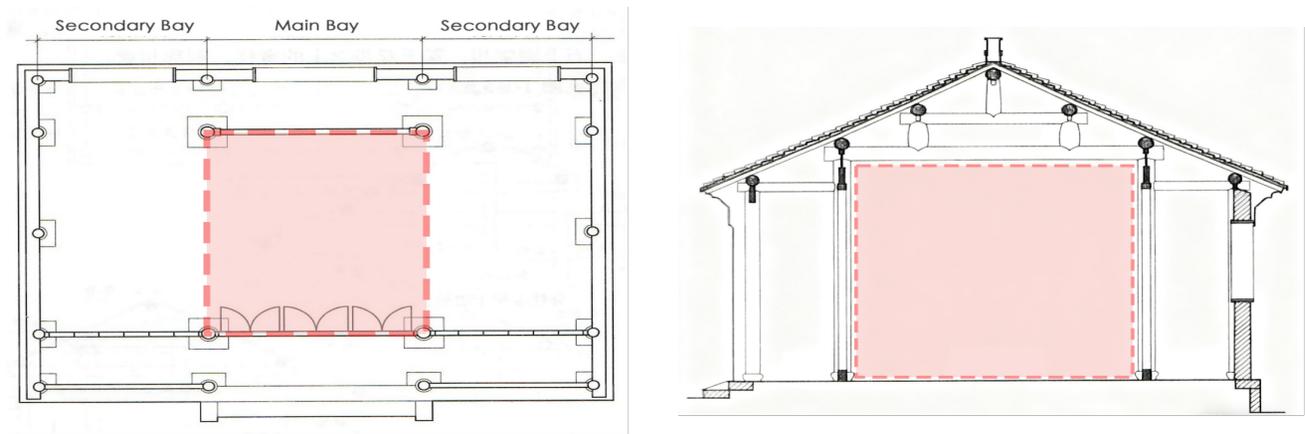


Figure 3. Schematic illustration of the position of “jian” in the plan and section of ancient Chinese architecture.

The space between the four columns in the ancient Chinese architecture is called “jian”, which is the basic spatial unit of Chinese architectural space. As can be seen from the **Figure 3**, it constitutes a complete structural system. Four vertical columns bear the vertical loads, while the horizontal beams and rafters bear the horizontal loads and facilitate the force transmission. This unit is self-similar; regardless of the size of the building, the logical structure of its basic composition is consistent. Moreover, this unit has the characteristic of iterative generation and can be formed into more complex spaces through repetition and combination.

From the perspective of fractal theory, “jian” can be regarded as the “fractal element” of the spatial structure in traditional Chinese architecture. This fractal element has the following characteristics: clear structural logic, uniform and regular form, and flexible combination methods. It is precisely these characteristics that enable ancient Chinese architecture to generate rich and diverse architectural forms through simple iterative rules.

2.3. Spatial iteration from single buildings to courtyards

Based on the basic spatial unit “jian”, ancient Chinese architecture forms a complete single building through horizontal and vertical iterations.

Horizontal iteration involves repeating the same beam frame units in the width direction. For example, a three-bay building is arranged with three identical “jian” in the width direction. This iteration is not a simple replication but is adjusted appropriately according to the usage function and hierarchical system. The main room is usually larger, while the secondary bay is relatively smaller, but their structural logic remains consistent.

Vertical iteration expands the spatial scale by adding steps in the depth direction. A three-beam frame can be transformed into a five-beam frame by adding two steps, and then into a seven-beam frame by adding two more steps. During this iteration process, the basic beam frame relationship remains unchanged, only the scale changes. It is worth noting that this iteration often accompanies proportional scaling of component sizes, reflecting the scale invariance in fractal theory (**Figure 4**).

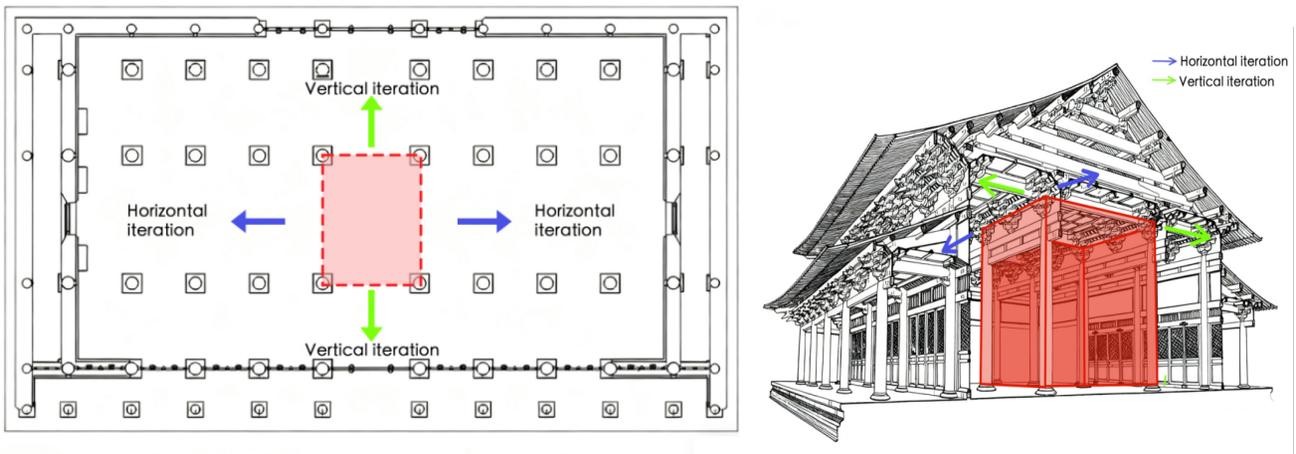


Figure 4. In a single building, horizontal and vertical iterations are carried out based on the “jian” concept.

The building units formed through the above iterative process further form courtyard spaces through enclosure, namely courtyard house. The courtyard house is the most typical spatial organization form in traditional Chinese architecture, and its basic feature is that four individual building units enclose a central courtyard, resulting in the form of a quadrangle or a patio. From the perspective of fractal theory, the courtyard is actually the iterative result of fractal elements in a two-dimensional plane (**Figure 5**). The Western Zhou ancestral temple site in Fengchu Village, Shaanxi Province (approximately 11th century BC) is the earliest discovered example of a courtyard building (**Figure 6**), indicating that the fractal thinking from “jian” to individual buildings and then to courtyards has a long tradition in the history of Chinese architecture.

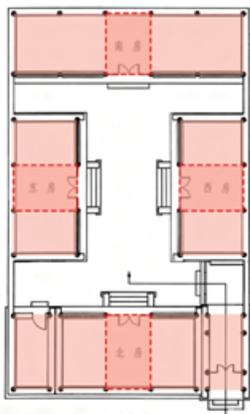


Figure 5. Plan diagram of Quarters House.

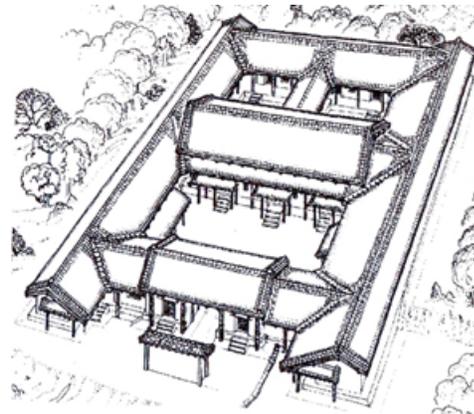


Figure 6. Reconstruction diagram of the Western Zhou Dynasty's Palace Temples (Adapted from “Fu Xinian’s Collection of Architectural History Papers”).

The courtyard space itself can also be iteratively transformed into a more complex self-similar space system. For instance, two courtyards arranged side by side can form a two-story courtyard, which in turn can develop into a three-story or four-story courtyard, and so on, creating a complex courtyard space along the depth direction; while in the horizontal direction, courtyards can also be arranged to form a cross-court form. The iterations in the “forward” and “cross” directions can ultimately result in a vast architectural complex.

2.4. The system fractality from settlement to city

The iterative process of courtyard space does not merely occur at the level of architectural complexes, but

extends to the urban scale as well. Taking the Yuan Dynasty capital as an example, its spatial structure exhibits distinct nested self-similarity characteristics: the outermost layer is the outer city, followed by the imperial city, the palace city (also known as the inner city), and finally numerous palace buildings (**Figure 7**). This “city within a city” spatial structure is precisely the nested self-similarity in the fractal theory.

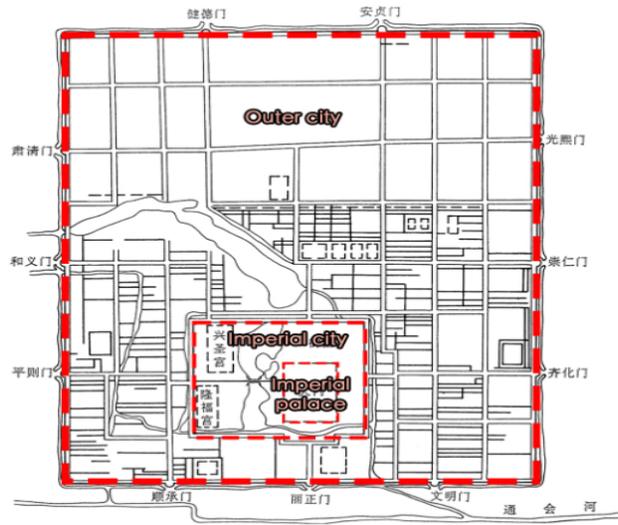


Figure 7. The outer city – imperial city – imperial palace system of the Yuan Dynasty Capital.

The “Zhou Li - Kaogongji” (a work written during the 7th century BC to 2nd century BC period), which is currently the earliest document on handicraft technology in China, records the planning system of the capital city: “The builders of the capital make it nine li (one li was about 300 paces) square, each side having three gates. Within are nine north-south and nine east-west streets, each street wide enough for nine carriages to pass.” This is an idealized urban spatial structure of the Western Zhou Dynasty (**Figure 8**). This way of dividing the city along the grid lines and roads, which form a strict layout and a grid system within each street area, is actually a regular fractal structure and maintains similar spatial logic at different scales. This is particularly prominent in the planning of Chang’an City during the Sui and Tang Dynasties (**Figure 9**).

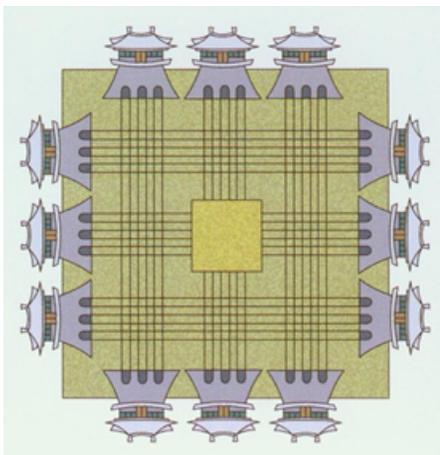


Figure 8. Plan Diagram of the City Layout in “Zhou Li: Kaogongji”.



Figure 9. Plan view of Chang’an City in Tang Dynasty.

2.5. Spatial manifestation of the “world” concept

The “world” concept in ancient China also exhibits fractal characteristics at the spatial level. The “world” is not a homogeneous space but a hierarchical system that gradually spreads from the center to the periphery. The emperor resides in the center of the world, while vassals are distributed in all directions, and barbarians are located at the periphery. This spatial concept has consistency in fractal terms with the composition logic of ancient Chinese architectural spaces.

The Chinese Pavilion at the 2014 Venice Architecture Biennale was themed “Beyond Mountains”. Through the iterative transformation of traditional Chinese residential spaces of “house - courtyard house - settlement”, it further explained the evolution process of “family - city - state - nature”, vividly demonstrating the fractal logic in traditional Chinese spatial concepts (Figure 10). The exhibition presented the traditional Chinese spatial aesthetics of a continuous scale system from tiny objects to the macroscopic natural environment through similar modules of “jian”, and it was the result of the iterative application of the “self-similar” space of fractal geometry (Figure 11).

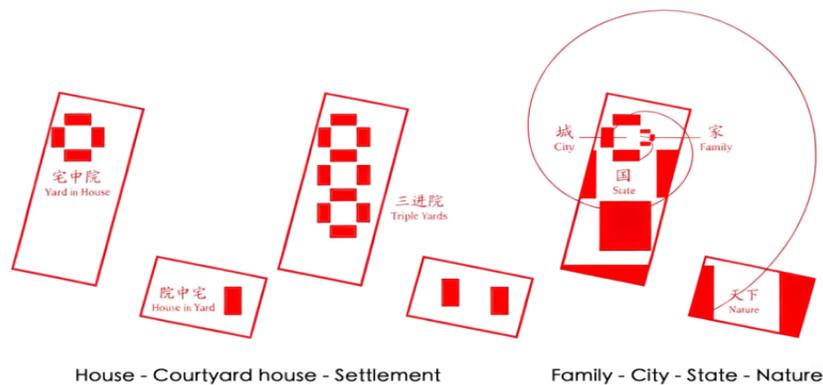


Figure 10. The fractal logic of “Beyond the Mountains” at the Venice Biennale.



Figure 11. In the “Beyond the Mountains” exhibition hall, various spatial forms are created by combining modules resembling “jian”.

3. Fractal characteristics of the structural construction of ancient Chinese architecture

3.1. Fractal iteration in the Dougong system

The dougong (bracket set) system is the most distinctive structural component of ancient Chinese wooden architecture and is also a Chinese architectural element with extremely obvious fractal characteristics. The

dougong system transfers the roof load to the columns through a layer-by-layer projection method, while creating deep eaves and rich facade effects.

From a fractal perspective, the dougong system has the following features:

3.1.1. Strict self-similarity

A complete dougong system is composed of basic components such as dou, gong, and ang, which repeat at different levels and form recursive structural relationships.

3.1.2. The composition follows clear iterative rules

Starting from the center of the eave column, the dougong projects outward to the inside and outside. Each layer projected out is an addition of new components on the basis of the previous layer, and the iterative rules are clear and strict^[5] (Figure 12).

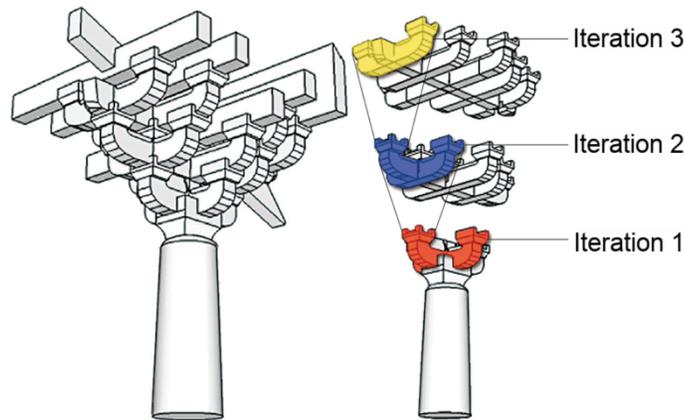


Figure 12. Iterative Diagram of Dougong (From Mao Yalong’s “Mimetic Architectural Design Based on Fractal Geometry”).

3.1.3. The complexity of the dougong system can be adjusted by controlling the number of iterations

Simple dougong system may have only one or two iterations, while complex dougong system can have as many as seven or eight iterations, which may create an extremely rich and diverse visual effect, yet the basic structural logic remains consistent throughout.

3.2. Fractal logic of the beam frame system

The beam frame system is the main load-bearing structure in ancient Chinese architecture, and its composition also exhibits distinct fractal characteristics. The fractal features of the beam frame system are mainly manifested in the following aspects:

3.2.1. The composition of the beam system follows a clear hierarchical structure

Starting from the most basic 5-purlin beam and the horizontal beam (3-purlin beam) above it, to the complex 7-purlin beam and 9-purlin beam, it is actually generated through iteration based on the basic structural units (Figure 3).

3.2.2. The scale relationship in the beam system exhibits self-similarity

In ancient Chinese architecture, the dimensions of each component of the beam system often have fixed proportional relationships that ensure the visual harmony and stability of the structure in different scales of the building.

3.3. Fractal representation of other building components

Apart from the dougong and the beam system, other components of ancient Chinese architecture also exhibit fractal characteristics.

The lattice of doors and windows is a typical example. The traditional lattice of doors and windows is often formed by basic geometric patterns (such as squares, octagons, hexagons, etc.) through repetition and combination, resulting in complex patterns. These patterns maintain self-similarity at different scales, creating a rich visual effect.

The roof tiles also have fractal characteristics. The basic components, such as round tile and flat tile, are formed by repeated laying to create the roof surface, and the curves of the roof are achieved through minor adjustments of the tiles. This “using simplicity to govern complexity” construction method is a manifestation of fractal thinking.

The fractal characteristics in the patterns of colored paintings are even more obvious. Traditional colored painting forms, such as Hexi colored painting and Xuanzi colored painting are all complex patterns formed by basic patterns through repetition, scaling, rotation, and other transformations, with obvious self-similarity.

4. The continuation and development of fractal thinking in modern architecture

4.1. The implications of fractal theory for modern architectural design

Fractal theory provides new ideas and methods for modern architectural design. It emphasizes the organic connection between parts and the whole, which offers a theoretical basis for handling the harmonious relationship between buildings and the environment. Through the study of traditional settlements, it was discovered that the spatial form of settlements maintains a high degree of fractal similarity to the natural terrain. This design concept of harmoniously coexisting with the natural environment has significant implications for modern architectural design.

The concept of scale hierarchy in fractal theory guides architectural detail design. Compared to traditional architecture, modern architecture often appears monotonous due to the lack of sufficient scale hierarchies. Fractal theory suggests that an excellent building should contain rich details at multiple scale levels, allowing observers to have a good visual experience at different distances.

In addition, the iterative generation method in fractal theory provides new tools for architectural form creation. Through computer-aided design, designers can use fractal iterative algorithms to generate complex and organic architectural forms, which has begun to be applied in the field of parametric design.

4.2. Application of fractal theory in architectural evaluation

Fractal theory not only guides architectural design but also provides a scientific quantitative tool for architectural evaluation. By calculating the fractal dimension of the building facade, the visual complexity and detail richness of the building can be objectively evaluated. Some related studies have shown that people usually

have an instinctive preference for patterns with a fractal dimension between 1.3 and 1.5, which provides a new perspective for architectural aesthetics research.

In the field of historical building protection and development, fractal theory also has significant application value. By comparing the fractal characteristics of new buildings with the historical environment, the harmony between the new buildings and the surrounding environment can be evaluated. For example, new buildings in historical environments use modern materials and new spatial layouts, but by analyzing the fractal characteristics of traditional facades and spaces and applying these characteristics to the new buildings, a good, harmonious relationship with the historical environment can still be maintained.

Disclosure statement

The author declares no conflict of interest.

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