Innovative design of caisson lotus pattern in Mogao grottoes based on shape grammar

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Abstract. The caisson lotus pattern in the Mogao Grottoes is an important symbol of Dunhuang culture, but its innovative design is very scarce. Simple mechanical reproduction cannot satisfy its spread and development in modern aesthetics. In this study, by analyzing the caisson lotus patterns in the Tang dynasty, clarifies its types and characteristics, extracts the lotus pattern structure as the initial model, and uses shape grammar to evolve into new patterns that have both the original lotus pattern structure characteristics and modern aesthetics. Finally, the fuzzy comprehensive evaluation method is used to evaluate the new lotus pattern, which proves the feasibility and effectiveness of the method in this paper, and provides new design ideas for the inheritance and innovative design of traditional lotus pattern.

1. Introduction
The Mogao grottoes are located in Dunhuang, it is more than 2,000 years old and is the most precious cultural and artistic treasure left on the Silk Road. Dunhuang Mogao Grottoes is famous for its gorgeous and colorful decorative pattern art. In its splendid art treasures, the large lotus pattern in the square area at the top of the cave becomes the focal point of the entire cave, this square area is also called caisson. As show in the figure1, the blue line area is called cession. The caisson lotus pattern of the Mogao caves in the Tang dynasty is exquisite in shape, rich in patterns and beautiful in color. It is the pearl of the Dunhuang pattern. However, due to natural and artificial factors, mural resources are gradually disappearing [1].

With the development of the traditional cultural revival movement, more young people began to pay attention to the return of traditional culture, and a large number of traditional patterns appeared in the design of modern cultural creative products [2]. A large number of cultural and creative products related to the caisson lotus pattern have appeared on the market today, and the impact of "fashion culture" and changes in the aesthetic needs of modern people have made simple imitation, mechanical copying, and rigid design of lotus patterns unable to meet the people's aesthetic needs. How to balance the relationship between the two, we need to start from the characteristics of lotus pattern, combined with modern innovative design methods, evolution and inheritance of a large number of new characteristics to meet the needs of the Times, not only retain the characteristics of traditional lotus pattern, but also have distinct characteristics of the Times.
Shape grammar (SG) was originally proposed by George Stiny and James Gips and used in painting and sculpture creation [3]. As a form deduction method, it is famous not only for the extraction of modeling features, but also for the design of modeling deduction on this basis, and for the generation of product design schemes with continuity style. At present, shape grammar has been successfully applied in the fields of architectural design [4-6] and product design [7-9], and its feasibility has been proved by a large number of practical cases. Some scholars applied this method to the innovative design of traditional patterns. For example, by decomposing the structure of Bosanghwamun, a traditional Korean pattern, extracting Islamic classic patterns, Chinese ethnic minority patterns as the initial shape, evolved a series of new patterns [10-12]. The above uses shape grammar rules to carry out innovative pattern design, which can better retain the characteristics of the pattern, but simply extract the features of the original pattern, and then carry out modeling evolution, the resulting pattern is not highly innovative. At the same time, there is also a lack of evaluation of the effect of pattern evolution, so it is difficult to verify the effectiveness of the method. In view of this, this study will be based on the characteristics of the lotus pattern structure, and make corresponding transformations as the initial shape, and then combine shape grammar to carry out innovative design on the caisson lotus pattern, and at the same time evaluate the design effect, so as to ensure the feasibility and effectiveness of the method in this article.

2. An overview of the caisson lotus pattern of Mogao Grottoes in the Tang Dynasty
In the Tang dynasty (618-907AD), the Chinese economy developed unprecedentedly, and the society was stable. The shape of the lotus decoration in Mogao Grottoes in this period is significantly plumper than in the past, and match with colorful auxiliary decorations to make people feel vivid, lively, gorgeous and plump. According to the collection of caisson lotus patterns and the summary and analysis of previous research results, caisson lotus pattern can be roughly divided into the petals are flat, the shape of the petals is round or square and the tip is pointed, eight or more petals, the simple and beautiful shape of the flat petal lotus is like 386 cave, and peach-shaped petal lotus as shown in 205 cave, petals are peach-shaped and decorated with inner-rolled moiré or outer-rolled moiré. There are also Baoxiang flower produced by the artist by transforming natural flowers such as lotus, peony and pomegranate, such as cave 335. In addition, the petals of the curl petal lotus is half-opened and half-closed bloom, the end of the petals curls toward the heart of the flower, such as cave 369, as shown in figure 2.
The lotus patterns of the caisson in the Mogao grottoes in Tang dynasty are diverse in form and rich in color, which have the characteristics of magnificence and plump, and fully show the prosperity and development of the Tang empire. Although the caisson lotus pattern is very decorative, but due to its luxurious and plump characteristics, to some extent it has not symbolized the aesthetic needs of modern people.

3. Innovative design of lotus pattern

3.1. The concept of shape grammar

Shape Grammar is a design method based on the calculation law. According to George Stiny's definition of shape grammar, it can be expressed as:

$$SG = (T, L, R, I)$$

Where: $T$ is the set of shapes; $L$ is the set of marks; $R$ is the set of inference rules, and $I$ is the set of initial shapes. In the inference process of the actual pattern, the initial shape is the typical feature extracted from the pattern. Its basic operation is to carry out the morphological evolution of the initial shape through certain rules [13]. Commonly used shape grammar inference rules include: move, replace, scale, add and delete, mirror, copy, rotate, and switch [14]. In order to inherit the shape image of the product in design, the application of scaling, rotation and switching operations can better realize the continuation of the shape style than simple movement, and the movement is often used for the local transformation of the curve.

3.2. Structure extraction of lotus pattern

In order to retain the characteristics of the traditional lotus pattern, this article uses the structure of the lotus pattern as the initial shape to evolve the pattern. The structure of lotus pattern is obtained by means of circle making, line drawing and intersection finding in islamic geometric patterns. Take the 321 cave lotus as an example to show the process of obtaining the pattern structure.

1) First, the sharp points A, B, and C, D of the outermost large petals are connected in a straight line, the two straight lines intersect at point O, and draw a circle with OA as the radius, as shown in figure 3 (a). It can be seen from the figure that the sharp points of the outermost large petals are all on the circumference.

2) Duplicate the line segment AB and rotate it by 45 degrees and 90 degrees respectively, as shown in figure 3 (b). The rotated line segments fall on other petals, and the petals are symmetrical structures with this line segment as the axis of symmetry. At the same time, the second layer of petals closer to the center also takes this line segment as the axis of symmetry, and the four petals in the center take two of the perpendicular line segments as the axis of symmetry.

3) Combine these 4 line segments, copy and rotate 22.5 degrees to get the effect shown in figure 3 (c). It can be seen from the figure that the eight small petals in the outermost layer are all on the line segment, and the petal has a symmetric structure with the line segment as the axis of symmetry. The 8
petals adjacent to the outer petals are also symmetrical structures with these four lines as the axis of symmetry.

4) Duplicate the outer circle and scale it at the highest and lowest points of each petal, as shown in figure 3 (d). The petals are in the area of these two rings.

5) Duplicate a line segment and place it at the critical turning point of the petal shape, and then connect the point where the circle and the line intersect to obtain the outer contour of the petal, as shown in figure 3 (e).

6) In the above way, get the shape of other petals and remove the extra lines, as shown in figure 3 (f).

It can be seen from the obtained lotus pattern structure diagram that the main structure of the pattern is consistent with the original picture, through the straight line connection between the key points, the contour features of each element shape are retained, and the internal details are deleted, making the pattern simple.

3.3. Evolution of lotus pattern

In this paper, R1 is copied, R2 is rotated, R3 is scaled, R4 is deleted as the evolution rule, and the lotus structure of cave 401 and cave 321 is used as the initial shape for evolution. The specific evolution process is shown in figure 4. For cave 401, because the lotus structure is relatively simple, new patterns are obtained by using multiple combinations of replication, rotation, and scaling rules. For cave 321, since the structure itself is already very complex, a new pattern can be obtained by simply removing the useless lines and circles with the simple deletion rule. In this way, the lotus patterns in other caves were evolved and a large number of new patterns were obtained.
3.4. Fuzzy evaluation of design effect

In order to verify whether the lotus pattern designed by shape grammar can meet the needs of modern consumers, at the same time, in order to seek a reasonable quantitative evaluation factor, this paper combines the characteristics of lotus pattern and selects a fuzzy comprehensive evaluation method to evaluate the new lotus pattern.

First, let three design experts select 6 of the 50 new lotus patterns generated according to the shape grammar, as shown in figure 5. Combined with the design features of the lotus pattern, the evaluation index is set as: E = {E1, E2, E3, ..., En}, (n = 4). According to the five preference scales, the review set is V = {V1 = very important, V2 = important, V3 = generally important, V4 = not important, V5 = very unimportant}. Using expert scoring method to determine the evaluation weight of each evaluation index of lotus pattern design, W = {0.3,0.2,0.3,0.2}, the details are shown in table 1.

![Figure 4. Evolution process of lotus pattern](image)

![Figure 5. Evaluation samples](image)

| Evaluation index | Evaluation index description                                      | Evaluation weight |
|------------------|-------------------------------------------------------------------|-------------------|
| E1               | Innovative, unique, in line with the modern aesthetic             | 0.3               |
| E2               | Shape neat, harmonious, with melody                               | 0.2               |
| E3               | both traditional characteristics and innovation                   | 0.3               |
| E4               | Suitable for use in modern products                               | 0.2               |

According to the evaluation indicators in table 1, an online questionnaire was prepared and distributed to 100 post-90s college students. Taking the new lotus pattern in cave 401 as an example, the scoring statistical results are shown in table 2.

Table 1. Evaluation index description and evaluation weight of lotus pattern
**Table 2.** Evaluation score for the new lotus pattern in cave 401

|   | V1 | V2 | V3 | V4 | V5 |
|---|----|----|----|----|----|
| E1| 46 | 24 | 10 | 13 | 7  |
| E2| 52 | 21 | 14 | 10 | 3  |
| E3| 49 | 32 | 12 | 5  | 2  |
| E4| 57 | 28 | 12 | 3  | 0  |

The fuzzy judgment matrix D of the design optimization solution is obtained from Table 2, namely:

\[ D = \begin{bmatrix}
0.46 & 0.24 & 0.10 & 0.13 & 0.07 \\
0.52 & 0.21 & 0.14 & 0.10 & 0.03 \\
0.49 & 0.32 & 0.12 & 0.05 & 0.02 \\
0.57 & 0.28 & 0.12 & 0.03 & 0
\end{bmatrix} \]

Then, the comprehensive evaluation model B can be obtained as follows:

\[ B = W \times D = \begin{bmatrix}
0.3 & 0.2 & 0.3 & 0.2 & 0.2
\end{bmatrix} \begin{bmatrix}
0.46 & 0.24 & 0.10 & 0.13 & 0.07 \\
0.52 & 0.21 & 0.14 & 0.10 & 0.03 \\
0.49 & 0.32 & 0.12 & 0.05 & 0.02 \\
0.57 & 0.28 & 0.12 & 0.03 & 0
\end{bmatrix} = \{0.503, 0.266, 0.118, 0.08, 0.033 \} \]

The evaluation results of the new lotus pattern in cave 401 are as follows: 50.3% think it is very good, 26.6% think it is good, 11.8% think it is generally good, 8% think it is bad and 3.3% think it is very bad.

**Table 3.** Comprehensive evaluation results of 6 new lotus patterns

| Cave number of new pattern | Very good | Good | Generally good | Bad | Very bad |
|---------------------------|-----------|------|----------------|-----|----------|
| 401                       | 50.3      | 2    | 6.6            | 11.8| 8        | 3.3     |
| 396                       | 52.9      | 3    | 2.3            | 8.3 | 4        | 2.2     |
| 321                       | 49.7      | 2    | 9.8            | 9.3 | 4        | 4.8     |
| 171                       | 61.8      | 3    | 1.4            | 3.6 | 2        | 0.5     |
| 392                       | 59.5      | 2    | 8.5            | 5.4 | 4        | 2.6     |
| 407                       | 65.4      | 2    | 7.7            | 3.4 | 2        | 1.1     |

It can be seen from Table 3 that 56.6% of post-90s students think that the design of the six new lotus patterns is very good, and the design of cave 407 is the best. Followed by caves 171 and 392, 61.8% and 59.5% of college students think that the design is very good. The proportion of those who think that the design is poor is below 5%. Among them, the design of cave 321 is low, but some 50% of college students think that the design is very good. In short, the new patterns evolved through shape grammar basically meet the aesthetic needs of post-90s college students.

**4. Conclusion**

1) By summarizing and analyzing the caisson lotus patterns in the Mogao Grottoes of the Tang Dynasty, it is concluded that the lotus patterns in the Tang Dynasty are not only rich in shape and diverse in form, but also have gorgeous colors and plump characteristics, which fully shows the prosperity of the Tang Dynasty.

2) Applying the shape grammar to the innovative design of the lotus pattern, for the selection of the initial shape, this article changes the traditional method of directly using the typical features or elements
of the pattern as the initial shape, but instead, the drawing method of making circles, drawing lines and finding intersections in Islamic geometric patterns is adopted to extract the structure of lotus patterns. This structure not only has the main features of lotus pattern, but also simplifies the shape of lotus pattern. Then use the lotus structure as the initial shape and combine the copy, rotation, scaling and deletion rules in the shape grammar to evolve the lotus pattern to obtain a series of new lotus patterns.

3) Through the fuzzy evaluation of the new lotus pattern by post-90s students, the results show that the new lotus pattern obtained by combining the shape grammar not only retains the structural characteristics of the traditional lotus pattern, but also has innovation and uniqueness, which are basically in line with post-90s students' favorite.

The method in this paper can also be inferred into the evolution and innovative design of other traditional patterns, which is conducive to the inheritance and development of traditional patterns.

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