

Research Progress on Curved Plates in China: Applications in Architecture

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Abstract: Curved surfaces can give plates a unique aesthetic effect and physical advantages in acoustics and optics. Assembling such curved plates can greatly improve the image of buildings and enrich their functions. It is thus not surprising to notice that their wide applications in designed or completed buildings in China have become a trend. Thus, this study offers a comprehensive summary of the application progress of curved plates in the architectural field from three aspects: image expression, acoustic characteristics, and optical characteristics. On this basis, future directions are proposed. The main findings or suggestions are as follows: (1) climate harshness has increased recently, and the safety of structures and materials and the coupling effect of the two must be fully considered when designing the shapes of curved surface buildings; (2) research on the mechanism and numerical calculation of curved diffuser systems with different sizes and curvatures needs to be further developed; and (3) experimental studies of various and complex curved plates and different conditions to explore their optimal reflectivity, transmittance, absorptivity, and other optical properties will be an important development direction.

Keywords: curved plate; surface; building elements; architectural appearance; architectural acoustics; architectural optics



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1. Introduction

The curved plate is a combination of function, technology, and image. Its mechanical properties, functions and forms can better meet people's needs for the expected performance, special functions, and aesthetic effects of various products [1,2]. With the development of the global economy, science and technology, and people's pursuit of diversification of industry and life, many more applications of curved surfaces have arisen, for example, architecture [3–5], transportation [6–8], aerospace [9–11], medical devices [12–14] and agricultural machinery fields [15–17], which cover almost all fields involving physical designs, devices, or objects.

As stated in the previous papers' preface [1,18] regarding the research history of curved plates, as early as 1813, Sophie Germain derived the correct expression of the thin plate with flexural vibration. In 1850, Kirchhoff presented the important Kirchhoff assumption in his paper "Equilibrium and movement of elastic circular plates" [19]. In the late 19th century, N. Aron and A. E. H. Love established the theory of plates and shells [20]. In the 20th century, Timoshenko published his Plate and Shell Theory [21,22] in 1940. In 1984, Wang et al. [1,23] studied the stability and vibration of laminated, sandwiched, and stiffened cylindrical plates. In 1991, Wang et al. [24] used the elastic-plastic finite element method considering large strain and took the crack tip opening angle as the fracture criterion to realize the numerical simulation of the entire propagation process, from crack initiation to instability, in a stiffened curved plate under bidirectional loading. In 2002, Stott et al. [25] studied the parameters affecting the stability of curved plates under heating conditions.

In 2008, Deng et al. [26] studied the influence of the initial clearance on the final welding deformation of asymmetric bent-plate structures. In 2011, Qin et al. [27] compared the anti-explosion impact performance of curved metal sandwich plates, flat sandwich plates, curved single-layer solid plates, and flat plates. Later, the same team [28] reported that the curvature of curved plates also had an impact on anti-explosion performance. In 2015, Ren et al. [29] reported the vibration characteristics of curved sandwich plates with square honeycomb cores, which provided a necessary theoretical reference for the dynamic optimization design of honeycomb sandwich curved-plate structures. It can be seen that these quite systematic theoretical mechanics analyses and laboratory test research have laid the foundation for the application in the field of architecture.

Meanwhile, also thanks to the development of three-dimensional (3D) design algorithms [30], structural calculation theory [31], and preparation and construction technology [32,33] in recent years, complex surfaces that only existed in the imagination in the past have begun to be gradually applied in modern architecture. The structural form of the curved surface allows full philosophical concepts to be expressed more freely. Additionally, curved surfaces have been fully studied and developed in the practice of architectural construction [34]. Naturally, a large number of curved surface building cases in China came into being. However, they are mostly displayed in the form of engineering reports that lack systematicity. Therefore, to develop curved plates and their applications in engineering more effectively and accurately, on the basis of previous papers [1,18] that the description, preparation methods, and mechanical properties of curved plates have been reviewed, this paper focuses on improving the application of curved plates in China for building image and physical properties (especially acoustics and optics). Finally, the future development directions of these fields are proposed.

2. Image Expression of Curved Plates

2.1. Classification of Architectural Images

In the 21st century, with the development of new materials and technologies, architecture has gradually broken through the shackles of traditional academism, and more design concepts and functional requirements have been represented [35]. Rationality and sensibility interweave in this process, and curved surfaces in buildings gradually show excellent expressive roles and practicability in modern architecture. The previous paper [1] provided theoretical classification based on the geometric and mathematical expressions of surfaces, but in this paper, we take actual Chinese curved surface building engineering cases as the research object and sort and compile them into a brand new classification system based on two dimensions, which are the design concept source and the role of curved plates as building elements in architecture (Figure 1, horizontal and vertical axes), as shown in 3×4 cases in Figure 1. The idea of the specific classification is as follows.

The appearance of curved surface buildings constitutes a “shape” that is accepted as a “symbol”, which means that the architectural image is not only a shape but also an internal concept that has a certain spirit or common physical representation [36]. Therefore, the design concept sources of curved surface buildings can be mainly divided into local culture, natural imagery, humanity imagery, and construction purposes (Figure 1, horizontal axis classification). For local culture, the most direct reference for architecture is the people living around the building. By conforming to local social customs and behavioral habits, buildings can obtain the most basic historical identity and arouse resonance [37]. For natural and humanity imagery, both are conceptual recurrences of certain phenomena. The former focuses on imitating creatures and merging into nature, with soft curved surfaces and affinity [3], while the latter focuses on the positive and enterprising spirit and conveys expectations of life [38]. For construction purposes, these imagery types show the actual functions of buildings and strengthen the expression of functions of buildings themselves according to the intuitive expression of the external image, which coincides with the connotation of functionalism [39]. Therefore, curved surface buildings are divided in detail on the horizontal axis, but it should be pointed out that a specific building can

have the ability to express multiple image relationships, but for the purpose of guiding design, this paper introduces a construction case that emphatically elucidates only the core image expression characteristics.

Elements usually need to perform a certain function to realize the value of their arrangement, mainly in load-bearing and space separation [40]. Therefore, the classification of curved surface buildings according to the vertical axis is based on the building element roles played by the curved plates, which are mainly divided into load-bearing elements, envelope enclosures, and internal partitions (Figure 1, vertical axis classification). Specifically, as load-bearing elements, curved plates primarily bear the main load of the building and are the major force-bearing structure of the building. As an envelope enclosure, curved surfaces separate internal and external spaces and directly contribute to the appearance of the building. As internal partitions, curved surfaces have the effect of effectively and reasonably zoning building functions. Similar to the aforementioned horizontal axis classification, in actual curved surface buildings, a certain element often has multiple roles. To systematically summarize, only the main function played by a curved surface will be discussed. In addition, since the vertical axis is clearly and obviously divided, it can also express curved plates' contributions to building the architectural image. Therefore, the following sections first address two aspects of curved plates, namely, as load-bearing elements and space partitions (including enclosures and internal partitions), and specifically analyze typical cases of curved surface buildings in China.



Figure 1. Classification of curved plates and typical architectural cases. Line 1: (a) Nanchang Wanda Mall blue and white porcelain buildings [41] and local pattern [42], (b) Yangzhou International Horticultural Expo-International Pavilion [43], (c) Shanghai Sanlian bookstore—Huangshan Taoyuan store [44], and (d) Guangzhou Xinghai Concert Hall; Line 2: (e) Building 14, School of Architecture, Xiangshan Campus, China Academy of Art [45], (f) Anaya “Cloud Centre” [46], (g) Shenzhen Science and Technology Museum [47], and (h) Harbin Polar Park [48]; Line 3: (i) Shenzhen Bay Super Headquarters Base C Tower [49] and typical Terraced fields in China, (j) Taichung Metropolitan Opera House [50] and the cave model [51], (k) Beijing Beigou village brick factory (b&B) [52] and typical brick kilns in China, and (l) Beijing the Playscape-Children’s Growth Centre [53].

2.2. As Load-Bearing Elements

A large curved surface can eliminate the boundary between the roof and sidewall so that the building is not limited by square edges and corners, and its performance is more diverse. Constructing a building with such a large curved surface requires a load-bearing design of the curved elements used [54,55]. To satisfy the requirements of load-bearing capacity, two types of curved surface structures, giant steel grid structures, and specially shaped concrete shell structures, were developed.

For a giant steel grid structure, the basic idea is to divide the large surface into many small units to adapt changes in the curvature of the surface and then to construct the surface by connecting each surface plate unit with the network frame, that is, converting large issues into small issues. For example, a large number of porcelain curved plates (approximately 45,000 in total) and ethylene-tetra-fluoro-ethylene (ETFE) curved plates (membranes) were used in the design of Nanchang Wanda Mall (Figure 1a) and Yangzhou International Horticultural Expo-International Pavilion (Figure 1b), respectively. The differences between the two buildings are as follows. (1) In the angle of force transmission, for the former, the load is directly transferred to the giant curved steel frame, and all the curved plate elements are not stressed. For the latter, the ETFE curved plates (membranes) are fixed onto the steel frame to form an air-cushion membrane structure and bear the load together. (2) Regarding the curved plate unit material, for the former, porcelain is obviously the best choice for imitation of the blue and white porcelain exterior tank wall, with a surface also printed with many beautiful traditional Chinese blue-and-white patterns, as pictured (Figure 1a), showing the ancient charm of China [42], which was known as the Porcelain Capital, fully combined with the characteristics of local Jiangxi porcelain culture. For the latter, the ETFE material is used to outline the appearance of the finless porpoise, which is an endangered species in China, and at the same time, it skillfully and vividly shows the movement of the finless porpoise “cruising” by virtue of its high transparency, which greatly reflects the harmony between humans and nature and reflects the characteristics of the building’s full combination of natural imagery.

The special-shaped concrete shell structure does not break the integrity of the large curved surface and does its best to serve the image expression of the whole building. For example, the Shanghai Sanlian Bookstore Huangshan Taoyuan store (Figure 1c) forms an overall upward-arching floor slab by folding longitudinal concrete curved slab strips. Combining this slab with the design of the building’s lower level, which is transparent and looks like flowing water, the ancient typical corridor bridge, the humanity imagery is depicted, also showing the craftsman spirit of ancient builders. The special-shaped concrete shell is also used in the Xinghai Concert Hall (Figure 1d), which adopts a reinforced-concrete hyperbolic-parabolic curved roof (the curved area is more than 2700 m²) and has great resistance to roof loading. From west to east, the south-casting surface and the platform on the second floor form a grand piano supporting the cover, which greatly reflects the purpose of construction. This shape informs people that the building is a concert hall at a glance.

The above two cases are great manifestations of the combination of power and shape. The arc steel grid has a light weight and high strength, and this design is convenient for inlaying curved plate units of various materials to create different textures. The special-shaped concrete shell structure retains the integrity of the large curved surface, coherently and naturally showing the image of the building as a whole.

2.3. *As Envelope Enclosures*

The position distribution of a surface in space separates the space. In modern architecture, curved surfaces have become the bridge of communication between architecture and the environment or people. When a curved surface is used as the envelope enclosure, it is directly exposed to the outside, forming the appearance of the building and directly expressing the architectural concept. When a curved surface is used as an internal partition, it not only plays the role of traditional functional partitioning but also strengthens the bilateral interaction between the building and the environment or people. The following correspond to the four different sources of design concepts, the characteristics of which are better illustrated by contrasting the case of envelope enclosure (Figure 1, line 2) with the case of internal separation (Figure 1, line 3).

In terms of reflecting local culture, the Xiangshan Campus of China Academy of Art (Figure 1e) used curved plates to protect the corrugated roof [45], which clearly and directly expressed the winding mountain roads in traditional landscape paintings of areas south of

the Yangtze River, and recycled local old bricks and tiles were used on the surface, which was an obvious symbol of local culture. In the stepped podium building of the Shenzhen Bay Super Headquarters Base C Tower (Figure 1i), curved surfaces create internal separation and then improve underground lighting, assist in filtering pollutants in the environment, strengthen the benign interactions between curved surfaces and the environment, and generate a unique local terraced landscape overall based on curved surfaces.

In terms of imitating natural imagery, the facade of the Qinhuangdao Anaya “Cloud Centre” (Figure 1f) building adopts ultra-white glass to construct curved surfaces, directly wrapping the building in the shape of clouds and creating the image of “a cloud floating in the forest”, which directly reflects the floating sense of the building. The Taichung Metropolitan Opera House (Figure 1j) creates a horizontal and vertical tubular space resembling a cave using 58 internal dividing curved plates (walls). With changes in lighting and natural light, visitors can feel as though they are in a cave and can hear different sounds in different locations [51,56,57], enhancing the interaction between people and the building.

In terms of imitating humanity imagery, the Shenzhen Science and Technology Museum (Figure 1g) adopts stainless-steel curved-plate enclosures of various colors to directly create an image of a “spaceship” sailing into the future, which is relevant to the contemporary interest in unidentified flying objects (UFOs) and contains future and high-tech humanity images. The b&B (Figure 1k) uses a curved surface of bricks and stones to integrate and divide the whole area and uses the purest embodiment technique to echo and distinguish the interactions between architectural space, landscape space, and nature in different proportions [52]. Because the b&B commemorated the former brick kiln factory and was rebuilt on this basis, it represents the Chinese people’s struggle in the 1970s and the corresponding human spirit of life.

In terms of construction purposes, Harbin Polar Park (Figure 1h) directly creates a vivid image of the lovely white whale swimming by a white curved envelope, which naturally reminds people of polar scenery and strengthens the theme of the polar museum. In Beijing, the Playscape-Children’s Growth Centre (Figure 1l) aims to help children grow. A topographically designed curved hill system connects the main entrances and exits of each building, while two semi-outdoor circular theaters are arranged at the base of the hill. The whole site is covered by an undulating mountain formed by surfaces, through which children can interact with the building in a benign way to feel the changes in speed and mountain undulation, which helps children cognize their senses and integration.

3. Acoustic Characteristics of Curved Plates

In China, the acoustic characteristics of curved plates are mainly applied to improve the indoor acoustic environment of theaters. In view of the strong systematicity of these features, this section first introduces the principle and then conducts a specific analysis based on the current development of theaters in China.

3.1. Principle of Surface Acoustic Design

Due to the different properties of sound waves at different scales, the propagation properties of acoustic waves should be considered when discussing the acoustic characteristics of curved plates. From the law of sound propagation in air, it can be seen that the wavelength is longer at low frequencies. Between 4 m and 5 m, waves show obvious diffraction characteristics when passing through some small-scale building elements or furniture (such as columns and chairs) and obvious reflection and diffusion characteristics when passing through large walls or floors [58]. At medium and high frequencies, the wavelength is short, which can produce diffusion and reflection effects on the surfaces of tiny elements. Since building elements have little influence on sound when sound waves diffract, this discussion will focus specifically on reflection and diffusion characteristics [58]. However, curved plates have a great influence on the sound propagation path due to their geometric characteristics. On the same scale, using the characteristics of reflection and diffusion mentioned above [58], curved plates can be embodied as concave sound

aggregation and convex sound diffusion in practical applications, with both applications presenting greater advantages than those of flat plates [59]. Therefore, when it is necessary to plan and adjust the sound path, curved plates may be a good choice.

The reflection of a sound source in a room mainly has three conditions: plane reflection, concave reflection, and convex reflection. As shown in Figure 2a, plane reflection can produce a certain degree of diffusion, while a convex surface forms a more obvious diffusion [59]. Full diffusion in the hall can distribute sound energy uniformly, smoothly improving the full interior sound field distribution of reverberation time attenuation, to ensure an appropriate early decay time, decrease the difference in sound level between the front and rear rows, and adjust the balance of clarity and fullness. It can also eliminate the possibility of quality defects, such as echoes and sound focusing acoustic, and suppress the acoustic feedback, which is very beneficial to improve the sound quality of the hall. This effect is widely used in architectural acoustics. A concave surface produces sound focusing, which will form the virtual sound source S' under certain circumstances. Energy is concentrated near the virtual sound source, resulting in insufficient sound pressure at a distance and resulting in uneven sound energy density in the hall, thereby affecting the audio-visual experience. This situation should be avoided as much as possible in practical applications. However, sound focusing, to a certain extent, can compensate for the problem of insufficient sound pressure in the back of an auditorium and improve the sound energy density in the back seating area by using sound focusing to balance the sound field of the entire auditorium [60].

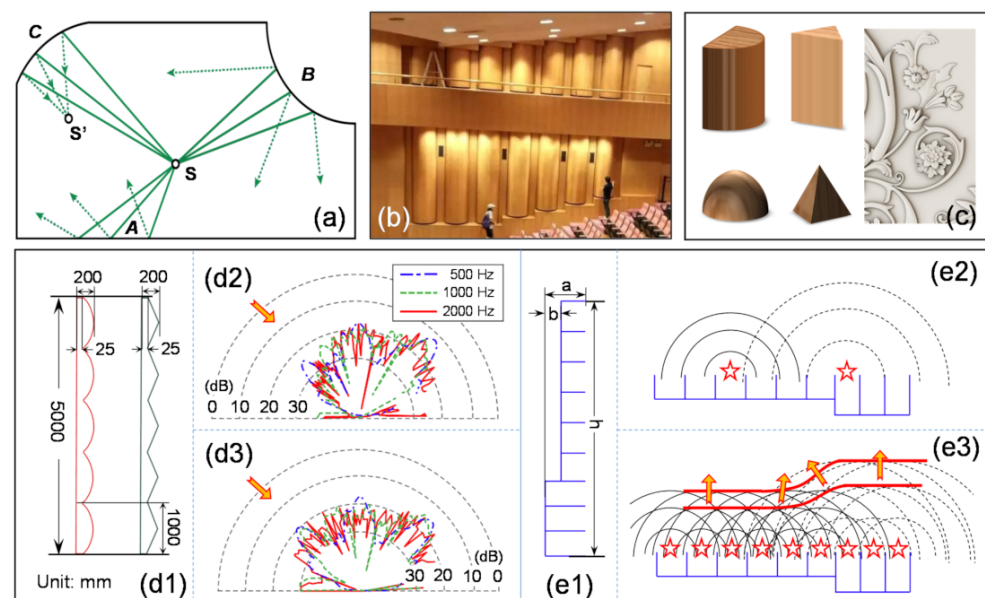


Figure 2. (a) Three basic situations of sound wave reflection indoors. (b) Concert hall sound diffuser group [61]. (c) Various forms of sound diffusers. Comparison of sound diffusion effects of triangular prism and semicylindrical diffusers: (d1) specific structure size, (d2) acoustic diffusion of triangular prisms, and (d3) acoustic diffusion of a semicylinder, where arrows indicate the direction in which sound waves are projected. Reflection effect of an incident plane wave in the local groove: (e1) structure schematic diagram, (e2) diagram of secondary-source radiation generated from independent grooves, and (e3) diagram of wavefront generated by multiple local secondary-source radiation [60], where the incident sound wave is not drawn and the asterisk indicates the secondary sound source.

When a curved surface is applied in the acoustic design of theaters, to achieve a certain sound diffusion effect, different geometric shapes can be constructed on the surface of the sidewall, back wall, and ceiling of the theater according to the requirements of interior art, such as a semipillar (triangular, semicylindrical, etc.) and embossed details (Figure 2b,c). Triangles and semicylinders have simple structures and great diffusion effects and are

widely used in the acoustic design of a theater. The effect of acoustic diffusion processing also depends on the size of the diffuser, and only when the size and appearance of the acoustic wave are diffused can the ideal diffusion effect be achieved. Therefore, Xiao [60] discussed the influence of the form and size of a diffuser on the diffusion effect, and research showed that the effect of a cylindrical diffuser is better than that of a triangular diffuser (Figure 2d). The diffusion effect of the diffuser increases with increasing sound frequency and diffuser size. Therefore, to ensure the diffusion of low-frequency sound, a diffuser should be of a certain size. Cylindrical diffusers have great advantages. If the size and shape design of a cylindrical diffuser are too simple, the reflection wavefront will interfere and affect sound diffusion. Therefore, to obtain the ideal diffusion effect over a wide frequency range, several diffusers of different sizes and shapes should be combined (Figure 2e).

Currently, many concert halls design acoustic diffusion walls according to quadratic residue in number theory [62]. When a reflection surface is broken (i.e., by a relief) or has grooves of different depths (Figure 2(e1)), acoustic energy can be effectively diffused. The principle is that when a sound wave reaches a wall, the sound wave propagates into the groove and groove surface to generate reflections, forming a secondary sound source (Figure 2(e2)). The time difference between the two contact interfaces leads to reflected sound waves of different phases, forming an irregular wavefront (Figure 2(e3)), which are superimposed together into local nondirectional reflections, and this type of nondirectional reflection benefits sound diffusion. On the whole, a large number of irregular concave and convex grooves form diffusion reflections of sound overall [63], which has better diffusion characteristics than conventional diffusers with general shapes and can obtain ideal diffusion effects over a wide frequency range [64]. Therefore, maximum length sequence (MLS) diffusers [65] and quadratic residue diffusers (QRDs) [66] were derived as supplements to architectural design. Overall structural designs of large sizes are combined with the undulation of the surface of the diffusion body to obtain a great sound diffusion effect [67], which is widely used in practical theater design. Therefore, the application of curved-surface acoustic characteristics is emphatically described in the following section based on typical domestic theaters.

3.2. Curved Surfaces in Theater Acoustic Design

The design of theaters has changed gradually with construction capacity. In the beginning, it was only possible to build square concert halls with small spans and simple shapes, but the heights of halls were increased due to the need for ventilation. The narrow and high shape resembled a shoebox, which is where the “shoe box-type concert hall” comes from [68]. With the improvement of architectural technology and the deepening of architectural acoustics studies, fan-type concert halls full of modern styles emerged, followed by unique and vineyard-type concert halls. In the process, changes in shape and acoustic requirements were compromised, and surfaces were gradually highlighted.

The shoebox-type concert hall is equipped with an acoustic system within a square space. In the evolution from classical to modern, its walls have changed from the original flannel carpets and exquisite reliefs to the modern curved surfaces. From empirical design to theoretical design, the reflection of a curved plate is used to greatly improve the distribution of sound fields. Since the shoe box-type concert hall itself has a great acoustic effect, most of the curved surface applications are as local fine-tuning processing [69]. In China, the most typical cases are the Shanghai Grand Theater and Guilin Grand Theater. The parallel side design provides a great spreading environment for sound reverberation. At the same time, to improve the effect of sound diffusion, a convex-arc reflective surface is adopted in the front sidewall and ceiling of the halls, local sidewalls are serrated diffusers, while balconies and their fence plates are, respectively, wavy lines and serrated (Figure 3a,b). However, compared with the classical design of the Shanghai Grand Theater, Guilin Grand Theater also incorporates local cultural characteristics into the design of the sound diffusion group. The roof adopts the structural form of the top of a cave, and the whole theater adopts

irregular natural streamline modeling, with locally uneven processing. On the side, the appearance of stalactites (Figure 3(b2)) is combined with the structural form of diffusers. The overall shape is irregular and wavy, and the local shape is similar to that of a stalactite. The concave and convex and thick and thin arrangements conform to the morphological rules of QRDs and MLS diffusers, respectively (Figure 3(b3)), meeting the requirements of the disordered arrangement of acoustic diffusers [70].

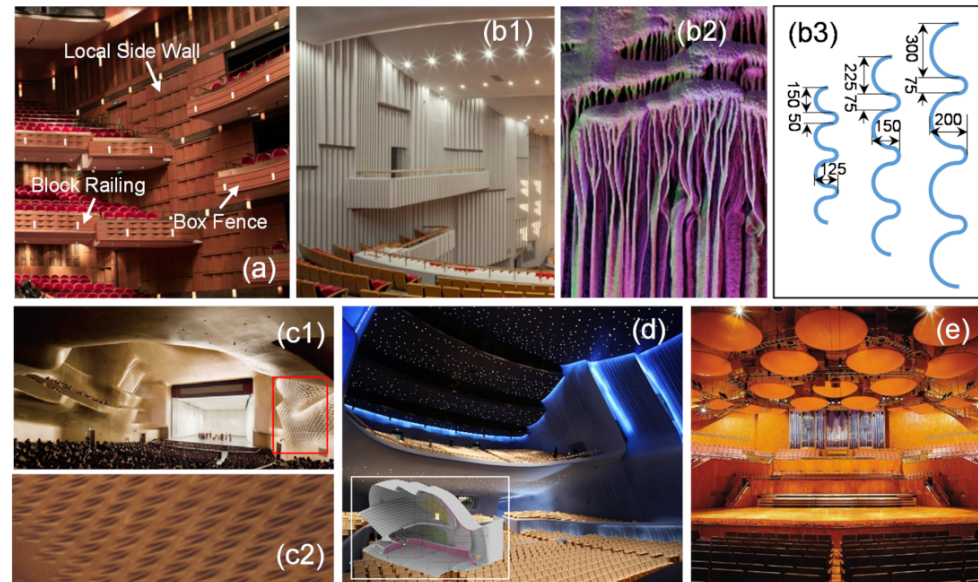


Figure 3. (a) Shanghai Grand Theater Auditorium [71]. The main theater of Guilin Grand Theater [72]: (b1) sidewall appearance, (b2) stalactites, the prototype of sidewall, and (b3) structural design of diffusers. Operatic Hall of Guangzhou Grand Theater [73]: (c1) side and surrounding walls, and (c2) surface texture. (d) Grand Theater of Zhuhai Grand Theater [74]. (e) Symphony Hall of Xinghai Concert Hall [75].

The fan-type theater conforms to the concept of modern architecture design, but due to its poor acoustic effect, it needs to seek help from the surface to improve the acoustics design in the development process, improve smooth transitions to be more natural, and decrease the sound field darkness. With this series of local changes, the theater can significantly improve the acoustic field distribution and compensate for defects in natural modeling. For example, Guangzhou, Zhuhai Grand Theater (Figure 3c,d), which caters to the “pearl river stone” and “the sun moon scallop” [76,77], has a theater building modeled after a fan-type arrangement. To meet the acoustic requirements, the sound diffusion group is arranged in an arc shape at the top of the theater to achieve sound focusing to a certain extent, providing sound reflection to the rear balcony, which in turn provides sound reflection to the bottom pool seats, making up for the weak sound intensity at the back of the theater. Each independent sound diffuser is a convex surface, which locally performs sound diffusion and equalizes the sound energy density in the theater. Combined with the microstructures of surface materials and electroacoustic compensation, indoor acoustic designs can be effectively improved [78]. Compared with the Zhuhai Grand Theater, the side and surrounding walls of the Guangzhou Grand Theater are arranged in a zigzag shape (Figure 3c) to effectively avoid the impact of plane reflection on sound quality [79,80]. The decorative surface of the whole theater adopts a “cat paw print” texture (Figure 3c), which avoids smooth surfaces, forming regular anti-acoustic wave arrays and a QRD anti-acoustic body [81], thus delivering shocking and nearly perfect effects, which are widely praised worldwide.

To enhance the audio-visual experience, the design of overall architecture spaces in vineyard-type theaters has abandoned inherent appearance forms of a surface. In a surface-disordered appearance, it achieves agreement between the distribution of the sound field

and the whole building layout in audio-visual design. From overall appearance to the internal architectural layout, the building reflects the concept of diffusion everywhere, providing top audio-visual enjoyment. The Xinghai Concert Hall (Figure 3e) adopts a “vineyard-type” irregular space arrangement. A spherical section reflector is set on the top surface, and cone-shaped and arc-shaped directional reflectors are set on the periphery [82]. The entire hall consists of various arc diffusers. The acoustic optimization effect is remarkable, the direct sound is clear, enough reverberation is achieved, high frequencies are very balanced, and the acoustic field distribution is uniform [70]. Without the aid of any sound amplifiers, the sound of the music played in the 1518 seats is almost the same (Figure 3b) [75], no matter the location of audience members. Built in 1988, it is still one of the most influential performance venues in China and one of the professional concert halls with the best sound in China [75].

4. Optical Characteristics of Curved Plates

As the famous architect Ieoh Ming Pei said, “Let the light do the design” [83]. Research of natural light and artificial light is very important in architectural design, and the former is more important—in addition to providing light, it also has a great impact on human physiology and psychology and can effectively save energy [84]. Therefore, this section mainly focuses on the design of natural lighting and takes the main structures and auxiliary elements in practical applications as objects to elaborate upon the optical characteristics of building curved plates. For the former, due to the large building volume, natural light sources are greatly affected by the shape, window layout, and other factors [85]; thus, the effects are further subdivided and discussed as side, top, and top-side combined daylighting. For the latter, this section mainly introduces the reflector and Light duct lighting systems, which are two promising lighting facilities in China.

4.1. Natural Lighting Design of the Main Structure

4.1.1. Side Daylighting

Side lighting of the main structure of a curved surface is mainly designed to optimize the layout of the plane, the essence of which is to use the curved surface to change the traditional angular layout of the building. There are two main purposes: one is to increase the contact surface between the building space and the outside world to obtain brighter light, and the other is to realize self-shading by blocking excessive light. For the first purpose, take Lize SOHO (Figure 4a, designed by the Zaha Hadid team) as an example. By “twisting” the tower around the atrium by 45°, a dislocated arrangement between floors is realized, with the bottom layer divided along the northeast and the top layer divided consistent with the street direction, allowing the central portion of each floor to enjoy natural light through the atrium (Figure 4(a2)) [86]. For the second purpose, curved surfaces are often applied to buildings in hot and arid areas, which is an application seldom seen in China at present. This section introduces Al Hamra Tower (Figure 4b) in the Kuwaiti Peninsula for a supplementary explanation. Al Hamra Tower utilizes the same layout method as Lize SOHO, with both using the technique of “reversal”, but unlike Lize SOHO’s simple overall (from bottom to top) reversal to a certain angle, it reverses the open part around the atrium and the reversal mode is given scientifically and accurately according to the dynamic variation of sunshine (Figure 4(b2)) [87]. The result is a successful response to the harsh desert climate, which may become an important design reference for areas such as Hainan in China.

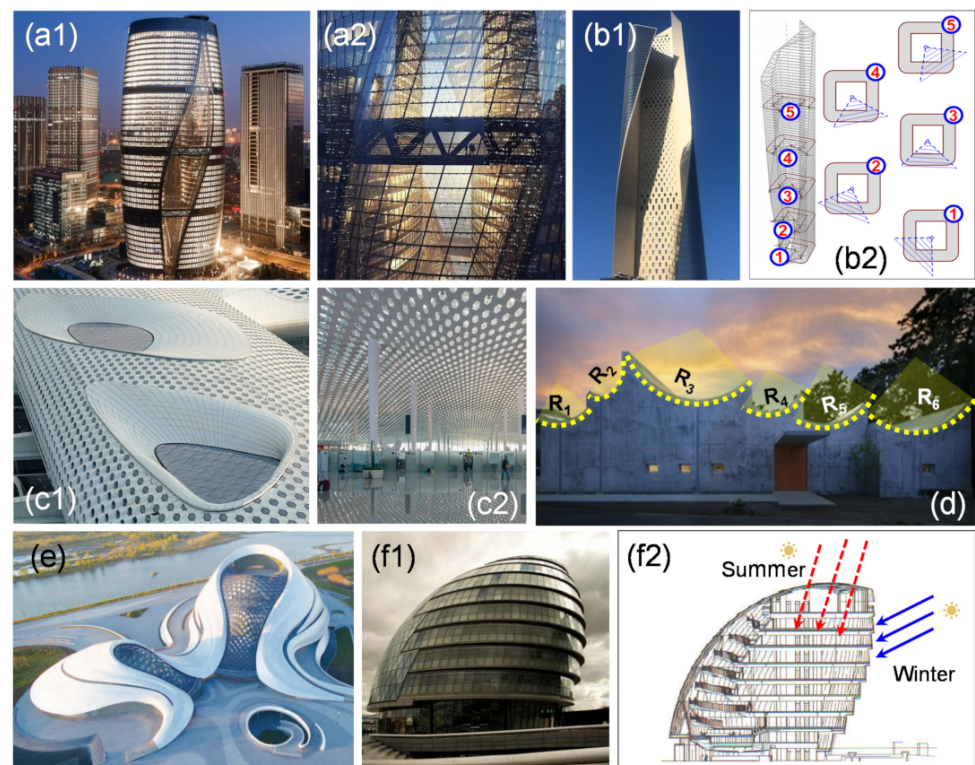


Figure 4. (a) Beijing Lize SOHO [88]: (a1) overall appearance and (a2) atrium. (b) Al Hamra Tower: (b1) overall appearance [89] and (b2) reverse design [90]. (c) Shenzhen Bao'an International Airport Terminal 3 [91]: (c1) lighting design and (c2) interior setting. (d) Shonan Christ Church [92]. (e) Harbin Grand Theater [93]. (f) London City Hall: (f1) overall appearance [94] and (f2) setback terrace design scheme [95].

4.1.2. Top Daylighting

Lighting design at the top of a curved main structure mainly concerns the skylight design, which mainly considers the scattering of natural light, that is, making it become softly scattered light. In practical applications, horizontal skylights and serrated skylights with special structures are used as models. The following is a detailed introduction of these two skylight lighting forms based on cases.

Although horizontal skylight structures are simple and decoratively flexible, special structures (or devices) are needed to provide light before scattering. Taking Terminal 3 of Shenzhen Bao'an International Airport as an example, the designer implemented a special double-layered curved skin with dense honeycombed openings in its cladding, thus forming thousands of small hexagonal skylights. At the same time, a number of horizontal large skylights were set and embellished (Figure 4(c1)). As a result, natural light is first reflected multiple times through the special double-layered structure and then converted into scattered light to uniformly illuminate the entire space through the horizontal skylight [96]. In addition, part of the building has two or three stories, and sunlight from the top of the space can provide direct illumination to meet the needs of natural lighting on the ground floor (Figure 4(c2)).

Zigzag skylights can scatter light directly and effectively only due to their curved shape. They are seldom used in China but are relatively mature and widely used in neighboring Japan. Taking the Shonan Christian Church as an example, Takeshi Hosaka designed the overall shapes of six curved roofs, with partial gaps on both sides of each roof to provide natural sunlight (Figure 4d). These curved surface structures successfully adapt to local daylight changes throughout the day. In the morning and at noon, the space is dominated by soft diffuse light suitable for prayer, and in the afternoon and evening, the

light pours in again. The walls are also deliberately set longitudinal grooves so that the curved beam top connection highlights and enhances the sense of light rhythm.

4.1.3. Top-Side Combined Daylighting

Buildings with a large curved surface often break the boundaries between the top and sides; thus, daylighting design needs to be directly optimized to improve the spatial optical effect and energy efficiency. The top side lighting design of the curved main structure uses a large area of the curved surface to form a whole external envelope structure from the sidewall and roof, which specifically manifests as an increase in the lighting window area or the formation of a self-shielding structure [97]. This study imitates the previous text and selects classic Chinese and foreign buildings (Harbin Grand Theater, Figure 4e; London City Hall, Figure 4f) for comparative analysis. To reduce the building area exposed to direct sunlight, both selected buildings are designed to tilt towards a certain direction in an irregular ellipsoid, but the differences between them are obvious. The former needed to consider dialogue and contact between two theater buildings and the integrity of a great large-scale special-shaped hyperbolic plate [98], rather than purely optical optimization of the surface design, which is a pity. The latter is based on accurate calculations of local solar angles and orbits and adopts the structural tilt 30° south and setback terrace design (Figure 4(f2)), which supplement each other. At high angles of the sun in the summer, the back form of the block structure guarantees that the rooms receive scattered light and avoid point-blank parallel light. When the sun angle is low in winter, the sun can precisely enter each floor, providing a stable top lighting source for the north facade of the building and improving the lighting of the building in winter, which shows a more flexible and perfect method of natural lighting [95].

4.2. Natural Lighting Design of Auxiliary Elements

When the lighting design of the main structure is limited or the optical system of the completed building needs to be transformed, it is also possible to utilize the optical characteristics of the building auxiliary elements to design the lighting system by changing the light path.

4.2.1. Curved-Plate Reflector

The curved reflector is a simple natural lighting auxiliary element. Its design is relatively simple, and its cost is low. The basic design principle is to change the characteristics of the light path using the curved surface to adjust the reflection of incident light into the depth of the interior, improve illumination from far windows in the interior, improve the illumination uniformity of the entire interior, and effectively reduce direct glare generated by the lighting surface [99]. This design was widely used in early museums, such as The Nordic Art Museum in Denmark (Figure 5(a1)) and the Meet Foundation Museum in France (Figure 5(a2)). Arc-shaped reflectors are used to diffuse natural light entering through the skylight into the museum, which not only protects exhibits but also enables artwork to have better display effects. Subsequently, as a lighting improvement measure, arc reflectors were applied in lighting renovations of classrooms. In China, Xu et al. [100] chose classrooms in several universities in Beijing for lighting improvement research and concluded that the setting of arc reflectors must fully consider the constraints of the original classroom space and structure, especially for classrooms with protruding structural columns and longitudinal beams (Figure 5(a3)), which should be designed in combination with light path simulation.

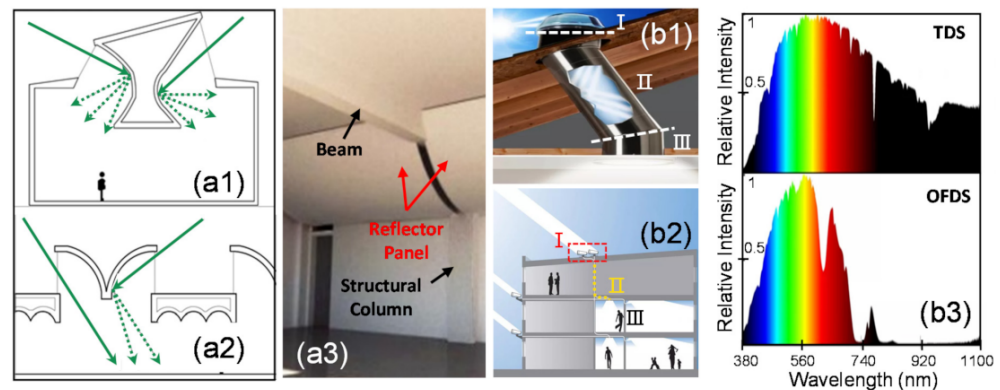


Figure 5. (a) Application of reflectors: (a1) Nordic Art Museum, Denmark [101]; (a2) The Meet Foundation Museum in France [101]; (a3) classrooms in a Chinese university [100]. (b) Light duct lighting system: (b1) tubular daylighting system (TDS) principle [102]; (b2) optical fiber daylighting system (OFDS) principle [103]; (b3) spectral analysis [104].

4.2.2. Light Duct Lighting System

As mentioned in Section 4.1.2, curved surface buildings that mainly rely on lighting from the top may lack effective natural lighting design in lower parts due to large height spaces or complex vertical structures. Therefore, a light duct lighting system represented by a tubular daylighting system (TDS) and an optical fiber daylighting system (OFDS) was developed. As shown in Figure 5(b1,b2), these two types of guided lighting systems mainly include three parts: the lighting area (I), transmission area (II), and diffuse reflection area (III) [105]. Among them, lighting areas and diffuse reflection areas are common between the two systems, and design research on lighting areas has developed rapidly in recent years [106], gradually developing from fixed system to solar tracking systems and tracking algorithms is constantly improving [107]. The remaining transmission area reflects the difference between the two systems. The TDS transmission area directly uses aluminum or silver as a reflection film material [108], which has a short transmission distance, but its advantage is that the construction technology is very low [109]. The OFDS, on the other hand, transmits light using fiber bundles [110] that can flexibly provide various focusing multiples (100–10,000). The transmission distance is very long, even up to more than 40 times that of the former, but the disadvantage is high technical difficulty [111]. As a result, the former is used in factories and gymnasiums, while the latter is used in offices and classrooms. For example, the gymnasium of the University of Science and Technology Beijing has adopted a TDS, and a total of 148 light tubes with a diameter of 530 mm are installed on the roof. With sufficient sunlight, relying only on natural light can fully meet any requirements of students in classes and sports training [112]. In addition, according to spectral analysis (Figure 5(b3)), the TDS is very similar to natural light, while the OFDS can filter infrared light and process natural light into a cold light source, which is more conducive to reducing the cooling load of air conditioning.

5. Future Directions

By reviewing the application examples of curved surfaces in the field of architecture, we display the unique aesthetic effect of the surface and the unique physical characteristics of the building. Based on real examples, we believe that with the development of the economy, science, and technology, combined with the function, technology, and image of curved plates, their flexible form and unique mechanical properties will be better able to meet the expected performance in the various products, achieving unique functions and aesthetic appearances. These functions and effects of curved plates stem from the complexity of the surface itself. Therefore, although research on surfaces has made great achievements, as mentioned above, some related basic design theories and engineering application research still need to be systematically and deeply performed.

5.1. Image Expression of Curved Plates

First, as mentioned above, the role of curved surface elements in buildings is closely related to the image created; that is, load-bearing curved surface elements are often used in large (full) curved surface buildings, while non-load-bearing curved elements are often used in small (partial) curved surface buildings. Especially for the former, there should be a systematic and complete structural design and optimization process for the rational arrangement of curved surface elements and the overall mechanical characteristics. The development of geometrically adjustable curved sandwich plates (such as honeycomb plates [113] and beetle elytron plates [114]) and other elements will be able to better adapt to various curved surface construction projects by virtue of their lightweight and high-strength characteristics, achieving broad application prospects. In addition, in recent years, abnormal climate conditions (i.e., large typhoons) have frequently appeared, and because curved surface buildings in China are primarily large and medium public buildings, their safety should be tested with scale models using techniques such as wind tunnels (wind resistance) and shaking tables (earthquake resistance). Meanwhile, the mechanical properties of a structure are closely related to its material. Therefore, considering the coupling effect of structure and material to ensure the safety of curved surface buildings is the direction of future research.

Second, with the development of cities and changes in people's living modes, the living environment in the city is not only confined to the interiors of buildings but also expands to broader urban public spaces. However, the lack of urban public activity spaces and the apathetic relationship between architecture and cities undoubtedly require architects to re-examine the relationship between architecture and the architectural community when engaged in architectural creation [115]. Therefore, it is more beneficial to generalize and classify the surface forms of various architectural individuals systematically and extract their characteristics. A "surface library" can be formed for use in design by imitating the mechanical design parts library, which will benefit popularization. At the same time, the application of surfaces is not confined to individual buildings; thus, building communities in city areas should be considered, with transitional spaces between "big" and "small" and "high" and "low" buildings to make the spaces of tall buildings that are close to the ground nearer to the small scale and surrounding of buildings, providing humanized places [116]. These will be research hotspots in the future.

Third, through morphological bionics, we can obtain 3D spatial surfaces from the forms of animals and plants. For example, the surface of a beetle's forewing has a lightweight and high strength, but the characteristics of its surface are still to be developed. Flowers are the representative of human favorites and beautiful plant imagery; thus, some beautiful natural petal surfaces, such as the use of petals, petals and stamens, petals and leaves, and even spatial geometric relationships between branches, can be amplified and used in buildings to obtain great bionic effects and form a green, ecological natural flower-imitating surface of buildings.

5.2. Acoustic Characteristics of Curved Plates

First, sufficient acoustic diffusion can improve the distribution of sound energy and sound fields inside theaters. The combination of curved diffusers with different sizes and curvatures combined with surface undulating structures will become a model (standard configuration) of sound diffusion system design. At the same time, the design will continue to develop towards the direction of optimizing surfaces to meet acoustic and aesthetic needs. However, most existing research is based on actual engineering design verification, and relevant theoretical and computer simulation (i.e., acoustic finite element simulation) research is still lacking. Therefore, for indoor acoustic effects, developing a mechanism and numerical calculation to optimize surfaces and improve indoor acoustic effects in theaters is one of the future development directions.

Second, with the flowering of stage performance forms, modern acoustic and electric technology is developing rapidly, especially sound source vocalization technology (such as

directional vocalization) and innovative layout schemes are in the ascendance, which is bound to drive innovation in acoustic effect creation. For each new sound source system, the development of the corresponding complete set of acoustic characteristics of curved plates or structures will be a research hotspot closely related to the acoustic industry in the future.

Third, architectural acoustics is not limited to the indoor acoustic design of theaters, and in fact, for most buildings, research on the partitioning of external noise is more urgent. At present, most newly built buildings in Chinese cities are high-rise structures, and because of the high population density, urban noise has become a problem that cannot be ignored. The characteristics of plane reflection and convex diffusion using curved plates are used to optimize building walls, roofs, and other envelope structures. This will become an important research direction in the future.

5.3. Optical Characteristics of Curved Plates

First, the natural light source is the sun, and its spatial position undergoes dynamic change relative to the earth. Compared with Chinese buildings, typical excellent curved surface buildings such as the Al Hamra tower and London City Hall flexibly integrate the dynamic change characteristics of natural light into their designs, which not only creates a soft and comfortable lighting environment but also reduces energy consumption. Therefore, the excellent architectural design strategy of optical-mechanical analysis of natural light sources and optimization of building light environmental quality and energy consumption should be developed, which will lay a foundation for establishing corresponding universal and systematic methods in the near future.

Second, zigzag skylights and curved reflectors have simple forms and are easy to use, and their improvement effects on architectural optics are remarkable, mainly because they make good use of their own curved surfaces. Therefore, maximizing these optical characteristics becomes a key focus. In fact, compared with the high requirement of optical testing accuracy in electronic chips and other fields, the required optical analysis accuracy in the construction field (especially in practical engineering) is lower. The cost of experiments examining different surface forms and working conditions is not high. Therefore, the direction of future research will include examining various and even more complex surface forms, designing various conditions, and conducting experimental research to maximize the reflectivity, transmittance, absorptivity, and other optical properties of elements.

Third, auxiliary elements such as optical guide systems have very distinct interdisciplinary characteristics, which are embodied in the creation of light-seeking and light-tracking algorithms and the design of materials such as lenses and optical fiber. With the upgrading of algorithms and the changing of materials, this auxiliary element will also undergo considerable development. Therefore, by developing the strengths of each similar discipline through proper integration, a lasting effect can be produced. This will also be a research hotspot in the future.

6. Conclusions

This review investigated the application of curved plates in the three aspects of image expression, acoustic characteristics, and optical characteristics with a focus on the Chinese architectural cases. The specific research results are as follows:

- (1) From the perspective of architectural image expression, a fresh classification system for curved plates has been established in two dimensions of the design concept source and their role as building elements. This systematic classification method can be used to guide the design of curved plates in buildings;
- (2) Based on the introduction to the principle of curved surface acoustic design, it focuses on the evolution of theater design form. Moreover, combined with the curved surface design cases of typical theaters in China, the curved surface acoustic characteristics in theaters are discussed;

- (3) The optical characteristics of the building are explained around the natural lighting design of the curved plates applied to the main structure of the building (side daylighting, top daylighting, and top-side combined daylighting) and auxiliary elements (curved-plate reflector and light duct lighting system).

Furthermore, on this basis, to develop curved plates and their applications in engineering more effectively and accurately, the following main future development directions are proposed:

- (1) In terms of architectural image expression, harsh climate conditions have increased in recent years. Future research will provide a better performance of curved surface building shapes on the basis of fully considering the coupling effect of structure and material.
- (2) In terms of architectural acoustics, research on the mechanism and numerical calculation of curved diffuser systems with different sizes and curvatures is the focus of future research.
- (3) In terms of architectural optics, experimental research on various and complex curved plates and conditions and exploring their optimal optical characteristics will be an important development direction.

Curved plates have a wide range of applications in Chinese architecture, and their applicability is expected to be broadened and optimized. This research has carefully summarized the applications of curved plates in image expression, acoustic characteristics, and optical characteristics using methods such as the establishment of a new classification and case analysis. Moreover, the development directions described in this paper will also attract researchers engaged in curved plates research and engineering applications.

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