

Article

Effects of Different Building Materials and Treatments on Sound Field Characteristics of the Concert Hall

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Abstract: The effects of different building materials on sound field characteristics of the concert hall were studied by experimental study and numerical simulations. A single non-directivity excitation sound source in situ test was carried out. The acoustic analysis model of the multifunctional concert hall was established. The reverberation time, the early decay time, the speech transmission index and the sound pressure level (SPL) were tested. The architectural treatment solutions with or without sound absorption in the design ceiling, sound absorption on the side walls, the influence of ceiling form on acoustic characteristics, and the acoustic characteristics of different positions on the first and second floors were analyzed, respectively. Simulation results show that there was little difference in reverberation time at different reception points by using the same treatment solutions, and the speech transmission index increased with the distance of the reception point. The language performance of the positions on the second was better than on the first floor. The SPL decreased with increasing distance from the receiving point. The ceiling form had no significant effects on the acoustic characteristics of the multifunctional concert hall, and the reverberation time was smaller when acoustic materials were used in the ceiling than the side walls. Meanwhile, the language transmission performance in multifunctional concert halls was improved. The difference between the maximum and minimum sound pressure levels for a sound-absorbing material ceiling is less than that of a non-sound-absorbing material.

Keywords: building materials; in situ test; numerical simulation; concrete; concert hall

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1. Introduction

Beginning with the theatres built for rituals in ancient Greece in the 7th century BC, performance-viewing architecture has continued to evolve, the designers have paid more attention to sound quality and increased the use of new technologies, new constructions, and construction materials to flexibly control and regulate the acoustical conditions [1–3]. Research has been widely carried out on the acoustic characteristics of performance-viewing buildings due to the needs of engineering practice in recent years.

The acoustic properties of the multifunctional concert hall of the Faculty of Music of the University of Zagreb were introduced [4]. A set of rotating cylinders is installed on the ceiling to meet the acoustic characteristics of the hall for different performances. The results show that the local diffusion coefficient changes with increasing source distance and is related to the sound absorption properties of the room interface [5]. The interior acoustic characteristics of historic theatres around the world were analyzed, and the acoustic parameters of four baroque theatres and one rococo theatre were measured [6]. The comparison revealed that the acoustics of a larger theatre is better for a given area. It can be found that in the mid- to high-frequency range of 500–8000 Hz, the reverberation time needs to be increased to eliminate unnecessary chattering echoes, thus optimizing the

acoustics and better meeting the intended purpose of the space [7]. An acoustic evaluation and objective live measurements of the circus theatre were conducted [8]. Trends in the sound fields of the Santa Gianna Beretta Molla Church and the Massimiliano Kolbe Church were studied. The introduction of absorbing benches is proposed for improving the acoustic properties of theatres and multipurpose auditoriums [9]. Since the publication of two international standards for testing the sound scattering properties of interfaces, there has been more in-depth research on the sound scattering characteristics of building interfaces and their measurement methods at home and abroad [10–12]. Field measurements and an acoustic comfort questionnaire survey on the acoustic comfort of a large railway station in Harbin were conducted [13]. The results showed a significant positive correlation between subjective comfort assessments and objective measures of the sound pressure level and reverberation time.

An analytical model of the three-dimensional sound field, generated by the interaction of incident sound waves with the surface of an acoustic porous medium, was established [14]. Huang studied the acoustic characteristics of the incomplete compartment plates and proposed a theoretical model for calculating the sound absorption coefficient [15]. Physical elements and a sound reinforcement system were used, both of which are designed to adapt room acoustics to the aesthetic requirements of the building [16–18]. The acoustic features and features of the hall under the light of the Wigmore Hall renovation project, and a good understanding of the acoustic behavior of the concave surface will make the acoustic designer more innovative [19]. It was found that the comparison of the calculated and measured impulse response seemed to be the first choice for evaluating room simulation software [20]. The sound intensity and reverberation time of six small concert halls in Cambridge were measured [21].

The effects of variable acoustics on the parameters in the hall are discussed. A numerical simulation of the acoustics of selected concert halls was carried out using CATT acoustics software [22,23]. An acoustic survey of the church in the modern architectural style used acoustic measurement methods to assess the acoustic quality of the nave [24]. The acoustic correction problem of the Historical Opera House was studied and found by replacing the textile tapestry with a diffuser plate [25]. A method is proposed to describe acoustic conditions in the performance space based on time–frequency and space–time representations to overcome the lack of detail in the standard analysis [26].

Song designed an acoustic metamaterial positioning cavity and found that the design has good application prospects by measuring the sound pressure level gain in air and water [27]. The acoustic performances of timber and timber–concrete floor solutions were assessed through an experimental campaign [28]. The beamforming techniques are employed to simulate and selectively measure the acoustic characteristics of three internationally well-known halls [29]. An initial index-based approach is proposed for assessing the acoustic quality of commercial spaces and buildings during the design process [30]. A 3D virtual model to study the sound field inside the church is proposed, analyzing the possibility of making proper acoustic corrections to reduce the value of reverberation time [31]. An acoustic survey was carried out to analyze the acoustic properties of the Idria Miner Theater and calculated and analyzed several acoustic parameters [32]. An automated program based on artificial neural networks was developed to estimate reverberation time to measure reverberation time in a room and evaluate its acoustic performance [33]. The convergent mixed-methods approach, merging both quantitative and qualitative analysis, provides a deep understanding of the role of the acoustic environment in enhancing the auditory experience [34–36].

The construction of concert halls has certain requirements for the sound of the sound, with a longer reverberation time, which makes the audience sound strong, rich, and full. The design of the concert hall needs to have a uniform sound field distribution and good sound diffusion characteristics, and avoid sound quality defects. Because each interface of the concert hall can generate acoustic reflexes, the noise is required to be locally absorbed as much as possible to avoid spreading to the stage and other directions.

The building site area, internal structure, and decoration materials all affect the acoustic parameters of the interior and it plays an important role in the improvement of sound quality. The complex internal spatial structure of the concert hall buildings, coupled with the many machines and equipment, cannot complete the acoustic design by empirical or theoretical analysis alone. Through a reasonable shape design and sound-absorbing material arrangement, the acoustic reflexes can be distributed reasonably in time and space, and the sound time and frequency characteristics of the design requirements can be satisfied.

Therefore, the effects of different building materials on sound field characteristics of the concert hall of the Baoji Grand Theatre were studied by experimental study and numerical simulations. The influence of different architectural treatments on the sound field parameters is studied by sound field simulation.

2. Project Overview

The Baoji Grand Theatre is located in Jintai District, Baoji City, China. The total building area is 41,300 m², specifically 25,800 m² above ground and 15,500 m² underground. The Baoji Grand Theater, which stands on the banks of the Weishui River, is a new urban cultural landmark of Baoji city. Figure 1 shows the images of the Baoji Grand Theater under construction and completed.



Figure 1. Images of Baoji Grand Theater. (a) Under construction; (b) completed; (c) night scene; (d) interior scene.

Figure 2 shows the layout of the Baoji Grand Theater. It is a large theatre mainly for opera and dance drama, and also meets the requirements for the use of various types of musicals, symphonies, local operas, and other large-scale performances and large conferences in the country and from abroad.

The functional buildings include a multifunctional concert hall, public theatre, general equipment, administration, business office and logistics, underground garage, and service support facilities, etc. The main structure is one story underground and four stories above ground, with independent foundations, and the underground part of the structure is in

the form of a frame shear wall [37,38]. The upper part is a rigid frame braced structure with a cast-in-place reinforced concrete beam and slab system for the floor cover. The theatre's multifunctional concert hall contains 1205 seats, including 870 seats on the first floor, 90 temporary seats, 225 seats on the second floor, and 20 private rooms; the effective volume is about $10,309 \text{ m}^3$, and the corresponding volume per seat is 8.5 m^3 , respectively.

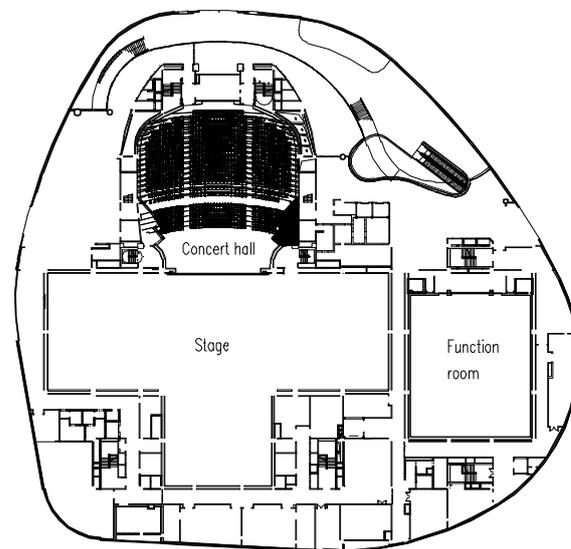


Figure 2. Top view of Baoji Grand Theater.

The architectural acoustic simulation software Odeon is based on the principles of geometric acoustic science. The combination of the virtual sound source method and sound line tracking method is used to simulate the computer sound field, which has a hearing function. The software can simulate the audio and hall acoustic science.

Figure 3 shows the multifunctional concert hall in plan and section drawings. The plan area is slightly horseshoe-shaped, with a maximum horizontal distance of 32 m from the stage entrance to the rear wall and a maximum width of 29.2 m. The shaped curved ceiling is used to meet the requirements of architectural modeling and acoustic characteristics. The first row of seats has a vertical height difference of 1.0 m from the stage, the superelevation value of each remaining row of sight lines is greater than 0.12 m to realize a barrier-free sightline design. Figure 4 shows the internal scenes of the concert hall in the Baoji Grand Theater. The maximum angle of view of the audience at the back row of the second-floor seats is no more than 30 degrees, the line of sight at the side of the second-floor seats is no more than 35 degrees, and the longest sight distance is 33 m.

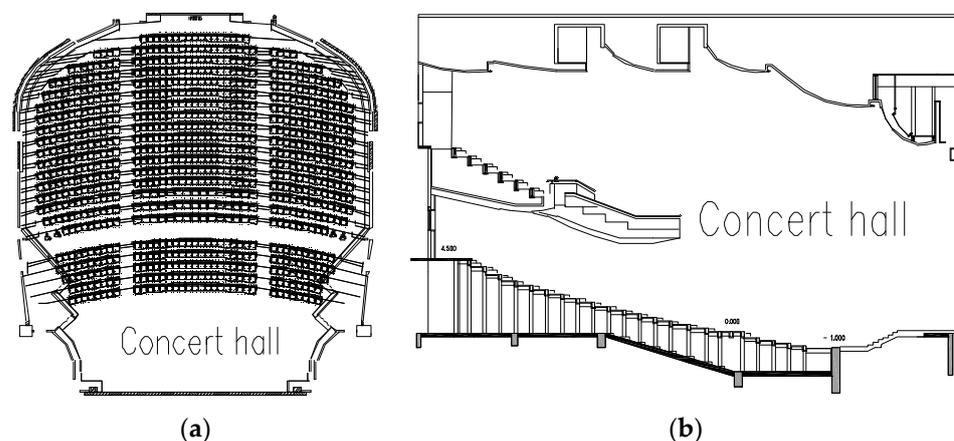


Figure 3. Drawings of the Baoji Grand Theater concert hall. (a) Plan drawing; (b) profile drawing.

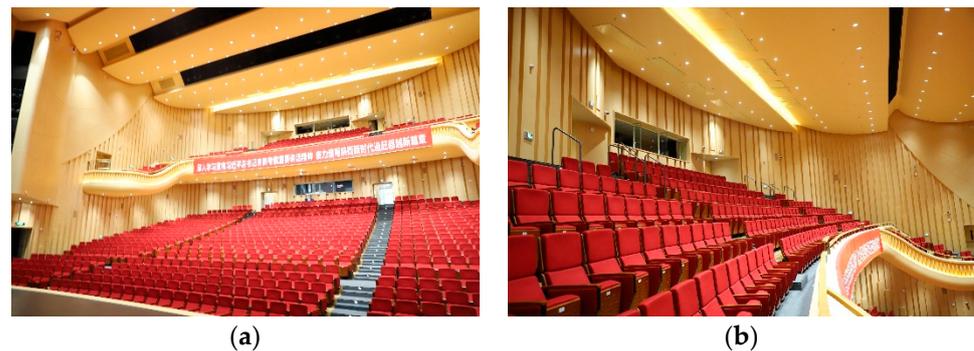


Figure 4. Scenes of the concert hall in the Baoji Grand Theater. (a) The first floor; (b) the second floor.

3. In Situ Test

A single non-directivity excitation sound source in situ test was carried out to determine the spatial sound field characteristics of the concert hall. Four parameters of the grand theatre were tested, namely the reverberation time (T_{30}), the early decay time (EDT), the speech transmission index (STI), and the sound pressure level (SPL). Figure 5 shows the results of the in situ acoustic characteristics tests. Reverberation time (T_{30}) refers to the time taken for sound pressure decay by 30 dB after the sound is stopped. Early decay time (EDT) refers to the rate at which the reverberation time decreases.

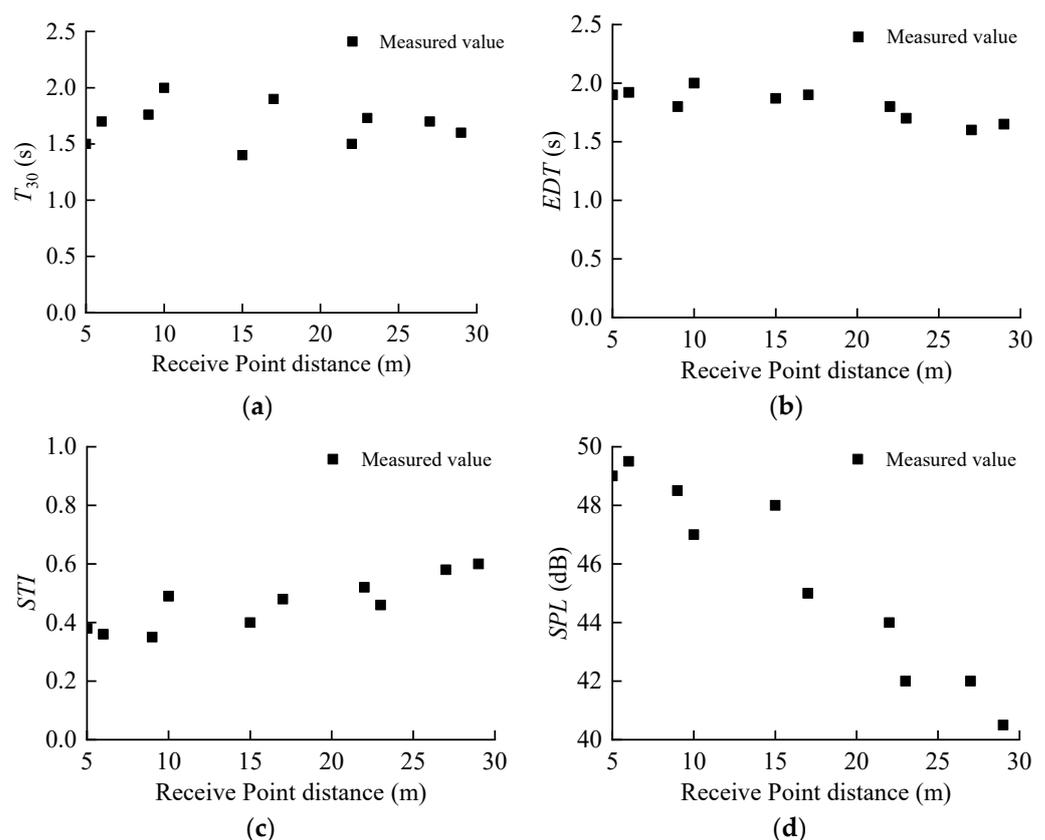


Figure 5. Results of the in situ acoustic characteristics tests. (a) the reverberation time at different receive points; (b) the EDT at different receive points; (c) the STI at different receive points; (d) the SPL at different receive points.

Figure 5a shows the test results of the reverberation time at different receive points. It can be observed that the reverberation time has no significant decrease with the increase of the distance from the sound source. The measured reverberation time T_{30} at each

point of the concert hall fluctuated around 1.6 s. It was found that a small number of points were greatly affected by the on-site test environment, and the theater shows good acoustic characteristics.

Figure 5b shows the test results of the early decay time (EDT) at different receive points. It can be seen that the overall EDT of the theater is relatively uniform. The measured EDT at each point of the concert hall ranged from 1.7 to 2.0.

Figure 5c shows the test results of the speech transmission index (STI) at different receive points. It can be found that the STI remains stable with increasing distance from the receiving point. Due to the special theater form, the value at the far end is slightly increased.

Figure 5d shows the test results of the sound pressure level (SPL) at different receive points. It can be found that the SPL decreases with increasing distance from the receiving point. Due to the influence of environmental noise, the SPL of the farther receiving point decreased significantly during field measurement.

4. Multifunctional Concert Hall Model and Related Parameters

4.1. Acoustic Model and Parameters

A model of the multipurpose concert hall was established using the 3D design software Sketch Up and then imported into Odeon to generate an acoustic analysis model. According to the architectural design scheme, the flooring material of the auditorium is thick solid wood and thick pine wood floorings. The sound reflective material of the ceiling and octagonal wall is a glass-fiber-reinforced gypsum board (GRG) with a thickness of more than 30 mm, and the sound reflective material in the side wall is a solid wood board with a thickness of 15 mm. The sound-absorbing material behind the side wall and the rear wall is a perforated wood board with a thickness of 15 mm and glass wool with a thickness of 50 mm. The absorption and scattering coefficients of the interface materials at different octave frequencies are shown in Table 1.

Table 1. Sound absorption and scattering coefficients of interface materials.

Section	Material	Interface Sound Absorption Coefficient at Each Octave						Scattering Coefficient
		125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz	
Ceilings	Glass-fiber-reinforced gypsum	0.03	0.01	0.01	0.01	0.01	0.01	0.05
Auditorium floor	Wooden floors	0.05	0.05	0.05	0.05	0.05	0.05	0.05
	Carpets	0.12	0.18	0.3	0.41	0.52	0.48	0.4
Auditorium wall	Wooden panels	0.15	0.12	0.1	0.08	0.08	0.08	0.1
	Wooden perforated plates	0.58	0.8	0.86	0.5	0.4	0.34	0.6
Stage entrance	-	0.3	0.35	0.4	0.45	0.5	0.55	0.3
Auditorium	Seats	0.32	0.43	0.49	0.48	0.51	0.54	0.7

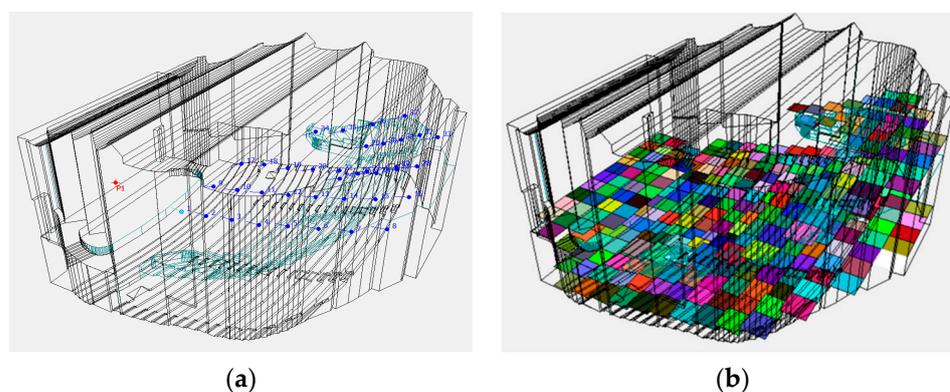
4.2. Spatial Location Acoustic Characteristics

The multifunctional concert hall has a complex architectural design with irregular planes and curved surfaces. Odeon's model has the x -axis, y -axis, and z -axis with width, length, and height directions, respectively. The acoustic field characteristics of the multifunctional concert hall are analyzed by arranging reception points at different locations in the model space. A non-directional source in the center of the stage has a height of 1.5 m from the stage; the coordinates are (15.100, −16.00, 2.500). Considering the axis symmetry of the multifunctional concert hall, three rows of receiving points were set up on the side of the first and second floor seats, where the first row of receiving points was located in the middle of the multifunctional concert hall, and the other two rows of receiving points were spaced 6 m apart along the x -axis; the three rows of receiving points were numbered as shown in Table 2.

Table 2. Numbers of reception points for first and second floor seats.

First Floor Receiving Points	x-axis Coordinate	y-axis Interval (m)	Second Floor Receiving Points	x-axis Coordinate	y-axis Interval (m)
C15	15.00	3.00	L15	15.00	1.50
C9	9.00	3.00	L9	9.00	1.50
C3	3.00	3.00	L3	3.00	3.00

The first row of receiving points in the first and second floor seats was 8.5 m and 25 m away from the sound source, respectively. The multifunctional concert hall was arranged with 37 reception points, and the sound sources and reception points are shown in Figure 6a. According to the quick estimation results of the reverberation time, the model impulse response length was set to 1500 ms, the number of sound lines was 3000, and the rest of the parameters were set by default. The first and second model were meshed at a height of 1.2 m from the ground to simulate the distribution and changes of each acoustic index of the whole multifunctional concert hall, as shown in Figure 6b.

**Figure 6.** Arrangement of sound source and receiving point. (a) Sound sources and reception points; (b) model meshing.

4.3. Analysis of Different Building Treatment Options

The use of flat treatments for suspended ceilings in multifunctional concert hall building designs simplified the process and was also an analytical method to simplify model analysis. In addition to the spectator area, the ceiling and side walls occupied a large surface area and the use of sound absorbing materials in the ceiling and side walls had a significant impact on the acoustic characteristics of the multifunctional concert hall. Using different combinations of sound absorption positions in the ceiling and side walls, six architectural treatment options can be obtained, as shown in Table 3. Figure 7 shows that the ceiling is glass-fiber-reinforced gypsum board when no acoustic material was used, the side walls were wood panels without acoustic material, and the acoustic material was perforated wood panels.

Table 3. Architectural design solutions.

Number	Ceiling Forms	Absorption Positions	Absorption Areas (m ²)
A1	Curved ceiling	Rear side wall + rear wall	658.42
A2	Curved ceiling	Ceiling + rear side wall + rear wall	1664.94
A3	Curved ceiling	In side wall + rear side wall + rear wall	1730.15
B1	Flat ceiling	Rear side wall + rear wall	639.06
B2	Flat ceiling	Ceiling + rear side wall + rear wall	1512.50
B3	Flat ceiling	In side wall + rear side wall + rear wall	1854.31

Note that A1, A2, and A3 are in the form of curved suspended ceilings, and B1, B2, and B3 are in the form of flat suspended ceilings.

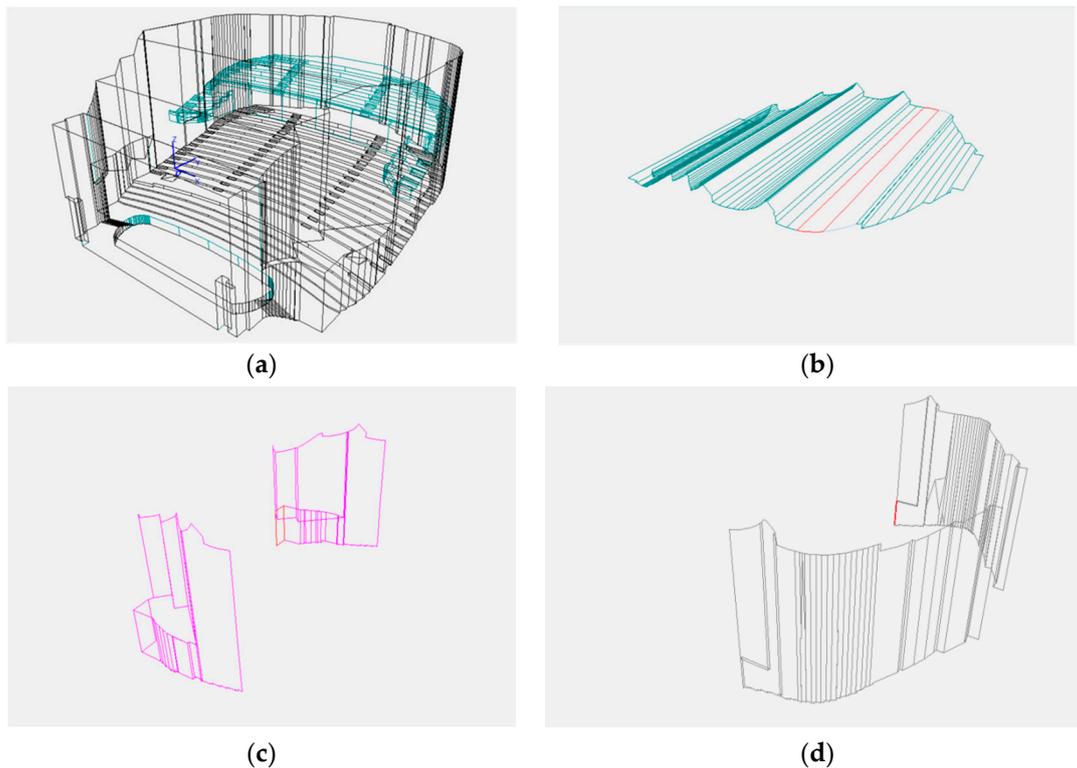


Figure 7. Ceiling plan treatment model. (a) Flat ceiling model; (b) curved ceiling; (c) side walls; (d) rear side wall.

5. Simulation Results and Analysis

5.1. Analysis of Acoustic Characteristics of Spatial Locations

Figure 8a shows the calculation results of the reverberation time at different frequencies obtained by quick estimation. In the quick estimation of the Sabine and Eyring formulas, it was assumed that the indoor acoustic field was completely diffused and the interface sound absorption coefficient was uniform. The sound absorption area and coefficient of the interface material were considered, but the space shape was not considered. Figure 8b shows the global estimation calculation results. The reverberation time obtained by the quick estimation was relatively small compared with the global estimation calculation results. For complex building structures, the reverberation time obtained by the quick estimation is different from the actual results.

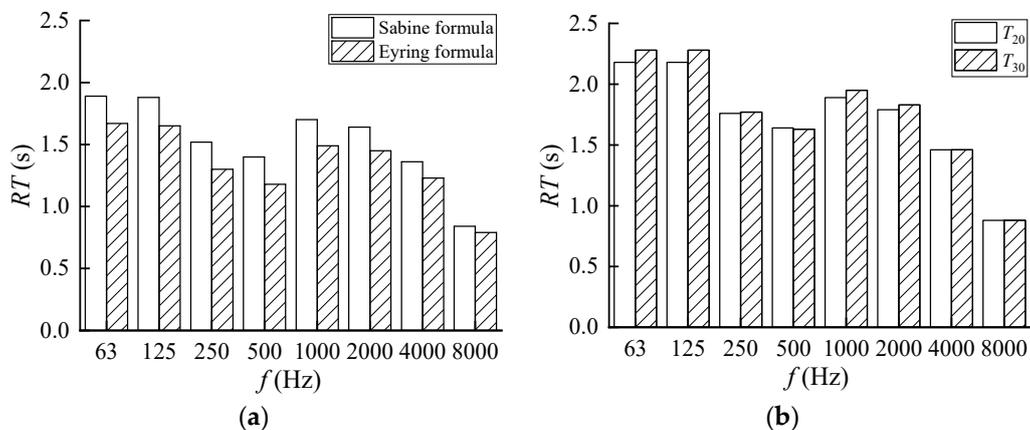


Figure 8. Reverberation time at different spatial positions. (a) Quick estimation; (b) global estimation.

The global estimation used the sound ray method to emit sound particles in random directions from the sound source. Odeon calculates the reverberation time of the model through the energy loss of the sound ray in the air and the energy loss caused by the absorption of the model surface. It can be seen that the calculation results of T_{20} and T_{30} at different frequencies are the same at an intermediate frequency. The mid-frequency reverberation time of the multifunctional concert hall is 1.63 s when the venue is empty, which satisfies the design requirements of 1.7 ± 0.1 s.

Figure 9 shows the distribution curve of the T_{30} at different locations in the concert hall. It can be seen that the multifunctional concert hall belongs to a uniform sound diffusion field. The reverberation time between the first and second floors does not change significantly with the increase in the distance from the receiving point. The overall early sound reflection effect of the multifunctional concert hall is great. The early decay time (EDT) is the reverberation time determined by the indoor sound field decay curve, which is closely related to subjective reverberation experience. It can better reflect the acoustic characteristics of a specific location in a room than T_{30} and is an objective indicator that reflects the characteristics of the indoor acoustic field. The EDT at different spatial positions calculated by Odeon does not decrease significantly when the distance between the receiving point was within 26 m. The sound source decreased slightly when the distance was 30 m, and there was no significant difference in the reverberation time between the first and second floors.

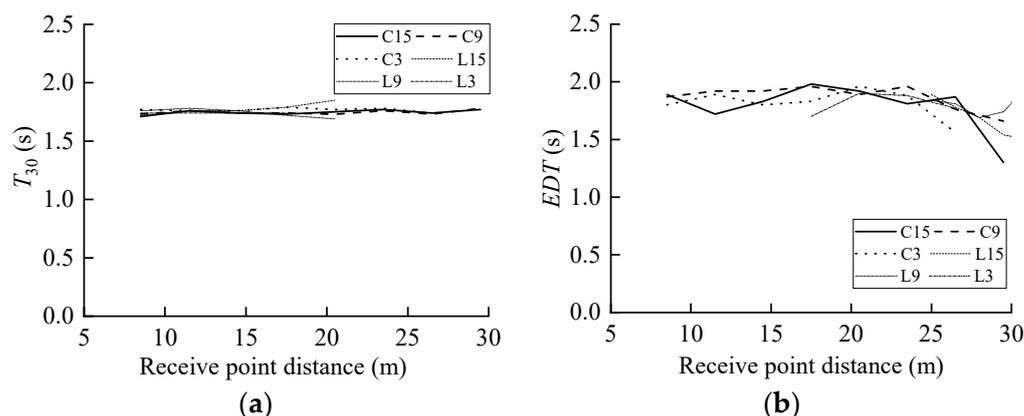


Figure 9. T_{30} and EDT at different locations in the concert hall. (a) Reverberation time T_{30} ; (b) early decay time.

It can be seen from Figure 10a that the clarity of language, D_{50} , firstly decreased and then increased by increasing the distance. The simulation result of the side of the concert hall is larger than the middle value. The language clarity simulation value of the first and second floors is not much different. The speech transmission index (STI) can be obtained through the modulation transfer function of the sound transmission system. Its value ranges from 0 to 1. The larger the value, the better the clarity. It can be seen from Figure 10b that with an increase in the sound source distance, the STI decreases and then increases. The values of the side of the first and second layers are significantly larger than the calculation results of the middle of the first layer. Due to the influence of the seats on the second floor, the speech intelligibility index and the speech transmission index of the first floor were affected to a certain extent, but the reduction of the acoustic index is little. The speech intelligibility of the multifunctional concert hall is great.

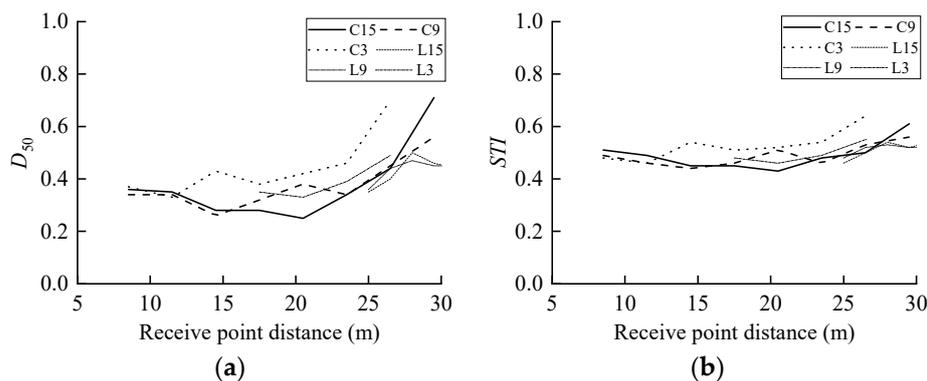


Figure 10. D_{50} and STI at different locations in the concert hall. (a) Clarity of speech; (b) speech transmission index.

The A-weighted sound pressure level (SPL) has an obvious effect on listening. It can be seen in Figure 11a, that as the distance from the sound source increases, the SPL gradually decreases. The middle of the first layer was reduced by 8 dB; the side of the first layer is reduced by 5.8 dB. It satisfies the maximum difference of 8 dB in the design of the concert hall. The SPL(A) of the second layer has a slight decrease, indicating that the sound field performance was better.

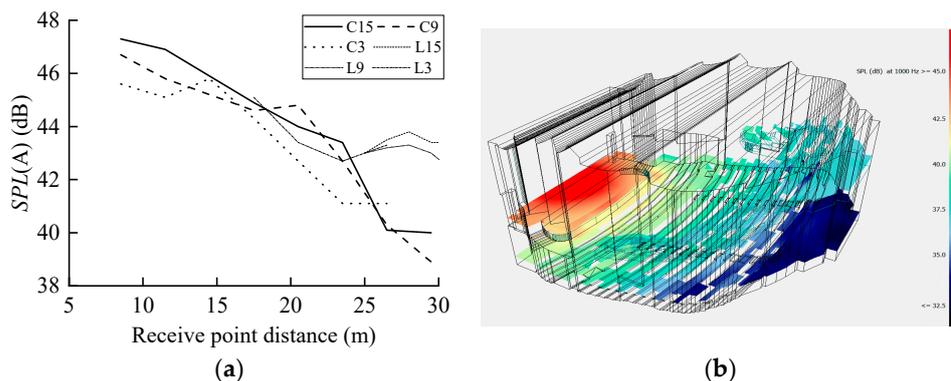


Figure 11. SPL(A) at different spatial positions. (a) Variation of SPL with distance; (b) variation of boost stage of the concert hall.

5.2. Analysis of Acoustic Characteristics of Building Treatments

Figure 12 compares the results of the Sabine formula and the T_{30} reverberation time simulations for the six building treatments. When the ceiling form is curved, the reverberation time for Option A2 is the smallest, followed by that for Option A3.

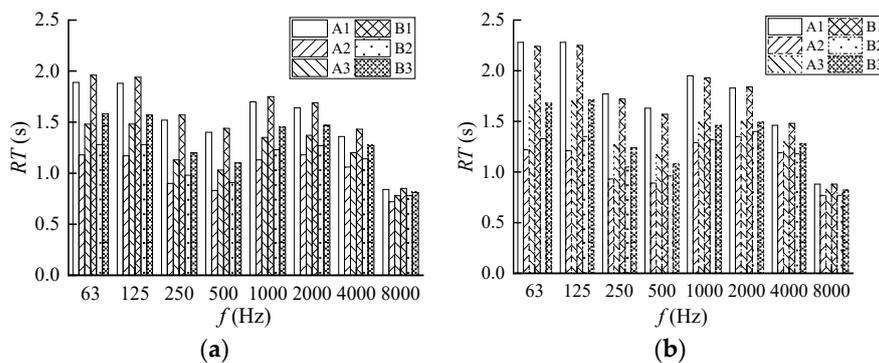


Figure 12. Reverberation time for different building treatments. (a) Quick estimates; (b) global estimate.

As the area in the side walls is smaller than the ceiling, treatment of the ceiling material is the better option when smaller reverberation times were required. From the global estimation results, it can be seen that the reverberation time does not change much from the curved form with the flat ceiling solution, indicating that the curved ceiling meets more requirements.

The curve of reverberation time as a function of distance from the sound reception point for the different building treatment options is shown in Figure 13. In A2 (curved ceiling replaced with acoustic material) the reverberation time at a distance of 10–15 m was greater than the reverberation time at other locations, while in other building solutions the reverberation time T_{30} changed little with the distance of the reception points. The EDT varied little within a distance of 20 m from the reception point and significantly and markedly decreased at 30 m. In general, the form of the ceiling had less influence on the reverberation time.

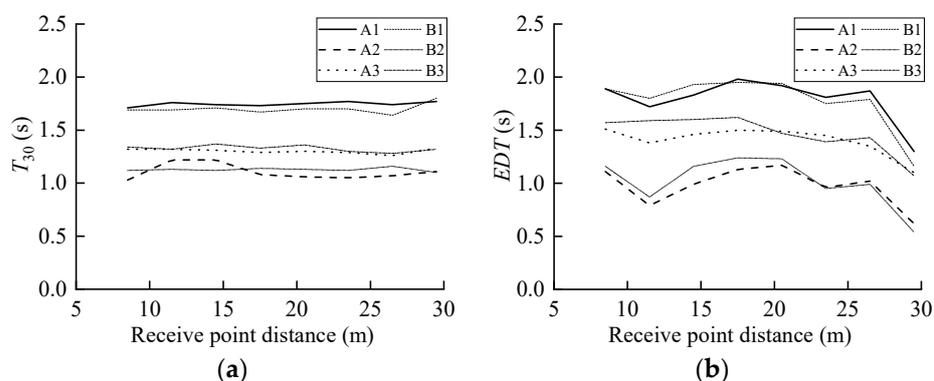


Figure 13. T_{30} and EDT for different building treatment schemes. (a) Reverberation time T_{30} ; (b) early decay time (EDT).

The variation of D_{50} and STI with distance from the sound source for the six building treatment options was shown in Figure 14. The D_{50} appeared to increase and then decrease as the distance with the receiver increased, with the lowest point being near 20 m. The clarity of speech in the first floor seats at this location was somewhat compromised by the effect of sound reflection from the second floor seat railings. The B1 solution had a definite effect on speech clarity, and the improvement in clarity was more pronounced when the ceiling was replaced with acoustic materials. The STI variation pattern was similar to the D_{50} , with a minimum STI value greater than 0.4, indicating great speech transmission in the multipurpose concert hall.

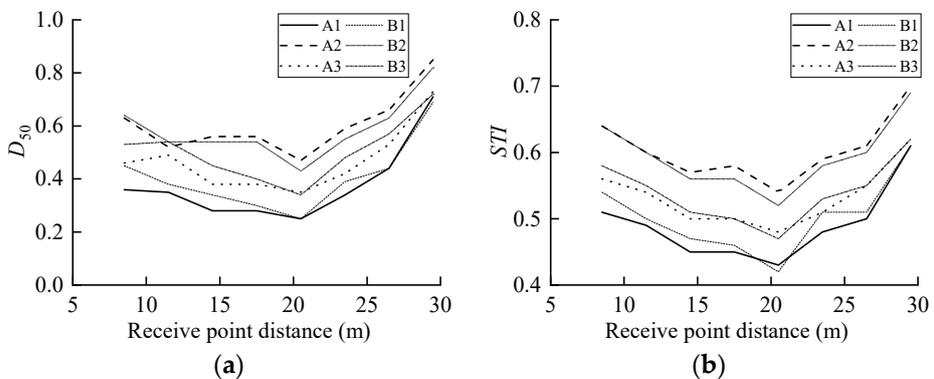


Figure 14. D_{50} and STI for different building treatments. (a) Clarity of speech; (b) speech transmission index.

Figure 15 shows the decay curves of SPL(A) with the distance for the different building treatment options. When the ceiling of the multifunctional concert hall was curved, the

sound pressure level attenuation rate increased when the ceiling and side walls are replaced with sound absorbing materials. Although the absorption surface area of the A3 side wall was larger than the A2 ceiling, the attenuation rate of the A2 solution was significantly greater than the A3 solution. When the ceiling changed to the flat form of the B1 solution, the sound attenuation rate was reduced compared to A1, and the weighted SPL(A) at the furthest receiving point A from the sound source was slightly greater than the A1 result.

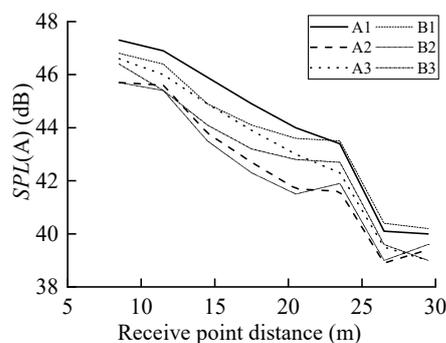


Figure 15. SPL(A) for different building treatments.

6. Conclusions

A three-dimensional acoustic Odeon model was established for the multifunctional concert hall of the Baoji Grand Theatre. The simulation results show that the reverberation time of the multifunctional concert hall meets the design requirements, and the acoustic field was evenly distributed with great clarity. The reverberation time at the multifunctional concert hall seats did not vary with distance. The speech transmission index decreased with increasing distance, with the side of the multifunctional concert hall having better speech clarity than the middle. The influence of different architectural elements increased with the distance. The second layer had a better reduction in sound quality than the first layer.

Through the Odeon acoustic simulation analysis, a reasonable arrangement of acoustic materials is obtained. The impact of the six building treatment options was discussed. Acoustic simulation results show that changing the curved ceiling to a flat ceiling reduced the reverberation time in the multifunctional concert hall, with little effect on speech clarity and transmission index, and resulted in a greater reduction in the sound pressure level at the same distance. The acoustic material used for the ceiling was more influential on the reverberation time than when it was used in the side walls, which will significantly affect the speech clarity and sound pressure level of the multifunctional concert hall.

In the design of the concert hall, since the side wall can provide the listeners and musicians with strong enough lateral early and late reflection sound, the auditorium has a uniform sound field distribution and good sound diffusion, avoiding sound quality defects. The acoustic simulation results indicated that the use of sound-absorbing materials for the side walls has little effect on the reverberation time of the theater. In the design of concert halls, the sound absorption material of the ceiling arrangement can improve the sound quality of the concert hall.

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