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JASA ARTICLE

Sound field characteristics and influencing factors of traditional Chinese interlocked timber-arched covered bridges

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ABSTRACT:

As an important type of traditional architecture in China, Chinese interlocked timber-arched covered (CITAC) bridges provide transportation functions, while interior spaces are also utilized for ritual activities. The unique spatial form of the CITAC bridge considerably influences the internal sound field. In this study, field measurements and acoustic simulations were conducted to determine the sound field characteristics of CITAC bridges and analyze the influencing factors. The results indicate that the mid-frequency reverberation time (RT_{30M}) of the four measured CITAC bridges ranged between 0.37 and 0.50 s. The spatial dimensions, enclosure structure systems, and occupancy of the CITAC bridges all influenced their sound fields: increasing the bridge length or adding gable walls on both sides significantly increased RT_{30M}; as the opening angle of the protective wooden panels beneath the eaves increased by 15°, the mid-frequency early decay time (EDT_M) inside the CITAC bridge decreased by approximately 10%. EDT_M and RT_{30M} were approximately 20% lower in the occupied condition than in the unoccupied condition. In addition to the cross-sectional aspect ratio, the influences of other spatial elements on the sound fields of CITAC bridges align with previous studies on the sound field characteristics of long spaces.

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I. INTRODUCTION

In this study, covered bridges refer to a special type of bridge with a traditional Chinese style structure built over a bridge deck across a river (Dai, 2012) and constructed of masonry, timber, reinforced concrete, or other materials. The Chinese interlocked timber-arched covered (CITAC) bridge, a well-established and regional type of ancient architecture (Xiao and Cheng, 2021), has a history of more than 900 years in China (Tang, 2010). Most of these bridges are located in Fujian and Zhejiang Provinces in southern China. Hundreds of CITAC bridges still exist (Chen *et al.*, 2021), most of which are well preserved and in normal use (Fig. 1), and dozens of these bridges have been listed as major historical and cultural sites that are protected at the national level because of their unique architectural value, historical significance, and cultural associations. In December 2024, the United Nations Educational, Scientific and Cultural Organization (UNESCO) added traditional designs and practices for building Chinese wooden arch bridges to its Representative List of Intangible Cultural Heritage of Humanity. Many traditional CITAC bridges have protective wooden panels on the exterior, which are designed at certain angles to shield the bridge from wind and rain erosion. These panels include small windows of various shapes. CITAC bridges are typically designed with niches for statues, where villagers can come to make wishes and pray for the blessings of the gods and immortals on regular days (Fig. 2). During festivals, these bridges are used as performance spaces, and villagers hold grand ritual activities inside these structures (Chen, 2011). Moreover, acoustic environments play a crucial role in creating atmospheres in various types of religious or folklore performance spaces worldwide (Zhang *et al.*, 2016; Zhang *et al.*, 2024), and the quality of the sound field influences the ability of a space to successfully host various ceremonial activities. However, in a CITAC bridge with a small cross-section and a long length, some acoustic challenges may occur during grand ritual activities. For example, will the audience at the ends of the CITAC bridge be able to hear the words of the singers in the middle of the bridge? Additionally, how do the acoustic parameters change when the bridge is occupied? These issues significantly impact the ritual experience of the participants. Thus, studies of the sound fields of CITAC bridges have significant academic and practical value.

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FIG. 1. Exterior of a CITAC bridge.

To date, no direct research has been conducted on the sound field characteristics of CITAC bridges. This review of related studies focused on three main areas: the architectural characteristics of CITAC bridges (history and structure), the sound field characteristics of traditional Chinese performance spaces, and analyzes of the sound field characteristics of various types of long spaces. In terms of the architectural characteristics of CITAC bridges, one study provided insights into the hidden knowledge and skills used to construct woven arch bridges, revealing the cultural characteristics of carpentry techniques (Liu, 2019). Additionally, in one study, load tests and finite element analyzes were conducted on a woven arch, and field tests and finite element analyzes were carried out on a real bridge (Yang *et al.*, 2019). In another study, the characteristics of various types of CITAC bridges were analyzed considering their structure and function (Dai, 2012).

Like other types of traditional Chinese architecture, CITAC bridges are built using a wooden structural system, including columns and beams, and wooden enclosure structure systems. Consequently, research on the sound fields of performance spaces in traditional Chinese architecture provides valuable reference points for the establishment of acoustic models of CITAC bridges. A previous study on traditional wooden theaters demonstrated that the desirable acoustic characteristics of traditional Chinese performance spaces are closely associated with their architectural form and construction materials, and these characteristics include strong early reflections and sufficient direct sound strength (Sun *et al.*, 2011). A previous study conducted by this research team involved field measurements and simulations of the Jiayintang Theater sound field in the Shenyang Imperial Palace, where the basic parameters of traditional courtyard theater sound fields were determined and the effects of spatial elements on the theater's sound field were analyzed (Zhang *et al.*, 2023). Moreover, the sound fields of the interior and courtyard of traditional Chinese Buddhist temples were explored in other studies (Zhang *et al.*, 2020a; Zhang *et al.*, 2020b). In another work, 21 traditional Chinese drum tower buildings were mapped and classified according to three characteristics: the shape of the plan, the elevation of the enclosing structure, and the aspect ratio of the longitudinal section. In addition, a correlation between the constructed drum tower structure and its sound field characteristics was established (Mao *et al.*, 2023). However, the spatial structures of CITAC bridges differ from those of traditional Chinese performance spaces, and the sound sources and acoustic receivers used during ritual activities inside the bridge are placed in different locations compared with those used in traditional performance spaces. Thus, these previous studies cannot provide a direct reference for understanding the sound fields of CITAC bridges.

FIG. 2. Ritual activities are held inside a CITAC bridge.

Acoustically speaking, the internal space of a CITAC bridge can be considered a long space, defined as a space in which one of the three-dimensional lengths is much larger than the lengths in the other two dimensions. An early study analyzed the sound fields of long spaces, such as corridors and tunnels, as semi-diffuse fields, with acoustic conditions between those of a free field (a sound field without reflections) and those of a diffuse field (a sound field in which the sound energy density is uniform and sound waves propagate randomly in all directions). However, the results obtained with sound pressure level equations greatly differed from the measurement results, which indicated that the semi-diffuse sound field theory is not applicable to long spaces (Yamamoto, 1961). Subsequently, Kang conducted a series of studies of long spaces. He demonstrated that the sound fields of long enclosures with either geometrical or diffuse reflection boundaries are not diffuse sound fields, as assumed in classic room acoustical theory (Kang, 1996d). Additionally, he analyzed the sound field characteristics of long enclosed spaces via computer programs and image source models (Kang, 1996a,c,1997). Moreover, numerous scholars have extensively researched long spaces, primarily underground stations (Kang, 1996b; Nowicka, 2007b; Nowicka and Shröder, 2008; Yang and Shield, 2001), underground garages (Jin *et al.*, 2009), and tunnels (Li and Lu, 2005). The research methods included field measurements (Nowicka, 2007b), acoustic software simulations (Liu and Lu, 2010), physical scale models (Liu and Lu, 2009), and theoretical prediction models (Kang, 1999; Li and Lam, 2005). While these studies provided a comprehensive theoretical and practical foundation, the spatial forms and building materials of these structures differ significantly from those of traditional CITAC bridges. As a result, the findings of previous studies on the sound fields of long spaces cannot be directly applied in investigations of the sound fields of CITAC bridges.

In conclusion, while considerable related research has been conducted, analyzes of the sound field characteristics within the interior spaces of traditional CITAC bridges are lacking, particularly in the context of their use as performance or religious spaces; thus, the sound field characteristics of CITAC bridges are determined in this study through field measurements and acoustic simulations of representative bridges. In addition, the factors influencing the acoustic characteristics of CITAC bridges, such as spatial dimensions, enclosure structure systems, and bridge occupancy status, are investigated.

The following research questions are addressed: (1) What are the sound field characteristics of the interior spaces of CITAC bridges? (2) How do factors such as the spatial dimensions, enclosure structure systems, and occupancy of CITAC bridges—including the length and aspect ratio, the settings of protective wooden panels and gable walls, the use of suspended ceilings, paving materials, and occupancy status—affect the sound field characteristics of CITAC bridges? (3) What differentiates the sound field characteristics of CITAC bridges from those of traditional Eastern and Western performance spaces and religious spaces with similar scales or functions? (4) As long spaces, do the variation patterns of the acoustic parameters of the interior spaces of CITAC bridges correspond with those of other long spaces? The findings of this study improve our understanding of the sound field characteristics of CITAC bridges and offer insights for the comprehensive preservation of these buildings and similar historical buildings.

II. METHODS

A. Measurement objects and processes

Field measurements were conducted on four representative CITAC bridges to obtain their architectural geometric parameters and reverberation times (RT_{30}), including the Denglong Bridge in Fujian Province and the Shuangmen, Futian, and Lanxi Bridges in Zhejiang Province. These bridges were selected because their internal facilities and structures are well preserved, and they are still frequently used for ritual activities, thus ensuring the accuracy and reliability of field measurements. In addition, they exhibit diverse spatial forms, such as different entrance styles, the presence or absence of protective wooden panels, and various length ranges, thereby representing both the common characteristics and major variations of CITAC bridges (Fig. 3). The various characteristic parameters of these bridges are listed in Table I.

The measurement process was conducted in accordance with the specifications of ISO 3382-1 (ISO, 2009). As shown in Fig. 4, on the basis of the location of the singer during ritual activities, the sound source for each measurement was positioned at the center of the span in a niche for a statue or at the center of the entrance to the bridge. The distance from the sound source to the nearest reflecting surface was at least 1 m in all cases. The acoustic receivers were positioned at the centers of the spans near the sound source or at the centers between pairs of columns. The sound sources and receivers were set 1.5 m above the floor, with the distance between them exceeding 3 m. Owing to site constraints, the reverberation time was measured via a balloon burst as an impulse source (Fig. 5), with the balloon having a diameter of approximately 38–40 cm.

Previous studies have shown that the results obtained using a balloon burst as an impulse source closely match the results obtained from repeatable measurements (Manohare *et al.*, 2017). Additionally, a larger balloon radiates more energy, and a higher inflation level results in increased high-frequency content (Pätynen *et al.*, 2011). Although using a balloon burst as an impulse source may introduce inaccuracies in the low-frequency range (Seetharaman and Tarzia, 2012), mid-frequency signals (500 and 1000 Hz) near the sensitive frequency range of the human ear during ritual activities were mainly considered in this study. Any low-frequency errors within a certain range were therefore considered acceptable. This instrument was calibrated in advance, and the errors were within 0.3 dB; however, to minimize measurement errors, the reverberation time for each receiver was measured at least three times, and the average of these measurements was used in the analyses. Owing to the greater number of niches for statues on the Denglong Bridge than on the other three bridges, additional sound sources and acoustic receivers were deployed.

The acoustic parameters of the CITAC bridges were determined through measurements to guide adjustments in subsequent simulation parameters. The measurement processes for the four bridges were essentially the same. During the measurements, the bridges were unoccupied, and the surrounding environment was quiet. Before the measurements, background noise was first measured on each CITAC bridge. The maximum background noise levels in the six frequency bands (125 to 4 kHz) were 19.7, 22.2, 27.3, 28.2, 23.5, and 18.7 dB, respectively. The peak sound pressure level (SPL) produced by the balloon burst was at least 45 dB higher than the background noise in the corresponding frequency band, thus meeting the signal-to-noise ratio requirements specified in ISO 3382-1 (ISO, 2009).

B. Sound field simulation and verification

The acoustic software Odeon (version 14.00) was used in this study to simulate the sound fields of the CITAC bridges. The applicable object types in the software include the sound fields of closed buildings, semi-closed buildings, open squares, and other buildings (Christensen and Koutsouris, 2016; Peng and Fu, 2010). Scholars have used this software to simulate the sound fields of traditional Chinese buildings and have verified its accuracy (Zhang *et al.*, 2023; Zhang *et al.*, 2020a; Zhang *et al.*, 2020b; Mao *et al.*, 2023).

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FIG. 3. Interior and exterior views of four CITAC bridges: (a) Denglong Bridge, (b) Shuangmen Bridge, (c) Futian Bridge, and (d) Lanxi Bridge.

Before starting the simulation, the calculation parameters needed to be adjusted to match the CITAC bridge dimensions and the expected reverberation time, considering the characteristics of the Odeon software to minimize the errors caused by the software itself. Quick and global estimate functions were used to estimate the reverberation times of the acoustic models. There are two important parameters in the general setting of Odeon14: "impulse response length" and "number of late rays." The former should be two-thirds of the longest estimated reverberation time. This study was set to 1000 ms, whereas the latter initially adopted the most accurate mode: "precision." The other parameters were set according to the recommendations in the Odeon user manual.

The acoustic model for the CITAC bridge, which was built with Google Sketchup 2017, was input into Odeon14. The main acoustic parameters of each interface material in the acoustic model were the sound absorption and scattering coefficients. The sound absorption coefficients were set on the basis of previous results obtained by this research team from investigations of the sound fields of ancient Chinese buildings (Zhang *et al.*, 2023; Zhang *et al.*, 2020a; Zhang *et al.*, 2020b), and the scattering coefficients were set by observing the outer surface conditions of the materials. Then, by comparing the differences in the reverberation times between the simulation values calculated with Odeon and the field measurement values, a cross-validation of the acoustic models for the four CITAC bridges was conducted. This process involved several adjustments to the acoustic parameters to ensure that the simulation results accurately matched the measurements. Notably, as traditional Chinese architectural structures, CITAC bridges feature intricate components such as bucket arches and roofs. To ensure simulation efficiency, relatively comprehensive modeling was conducted for the primary structural components of the CITAC bridges, such as columns and protective wooden panels, whereas small and more complex elements, such as niches for statues, bucket arches and lanterns, were simplified during the acoustic modeling process. Special acoustic coefficients were assigned to these simplified elements to

TABLE I. Introduction to the characteristics of the four CITAC bridges.

Bridge name	Denglong Bridge	Shuangmen Bridge	Futian Bridge	Lanxi Bridge
Location	Fujian Province	Zhejiang Province	Zhejiang Province	Zhejiang Province
Year	1677 (Qing dynasty)	1024 (Song dynasty)	Year unknown (Song dynasty)	1574 (Ming dynasty)
Length (m)	38	11.2	16.5	48.1
Width (m)	4.9	4.3	4.8	5
Aspect ratio (height:width)	0.88:1	1.02:1	1:1	0.78:1
Number of spans[a]	15	5	5	19
Protective wooden panels	With	With	Without	With
Gable walls	With	Without	With	With
Ceiling	Without	Without	Without	Without
Paving material	Stone paving	Wooden paving	Stone paving	Stone paving
Entrance style	Side entry and direct entry through gable walls	Direct entry	Side entry	Direct entry through gable walls

[a]In traditional Chinese architecture, the space between two adjacent columns on the front facade of a building is referred to as the "span." The term "number of spans" indicates how many of these horizontal units are present along the front of the building.

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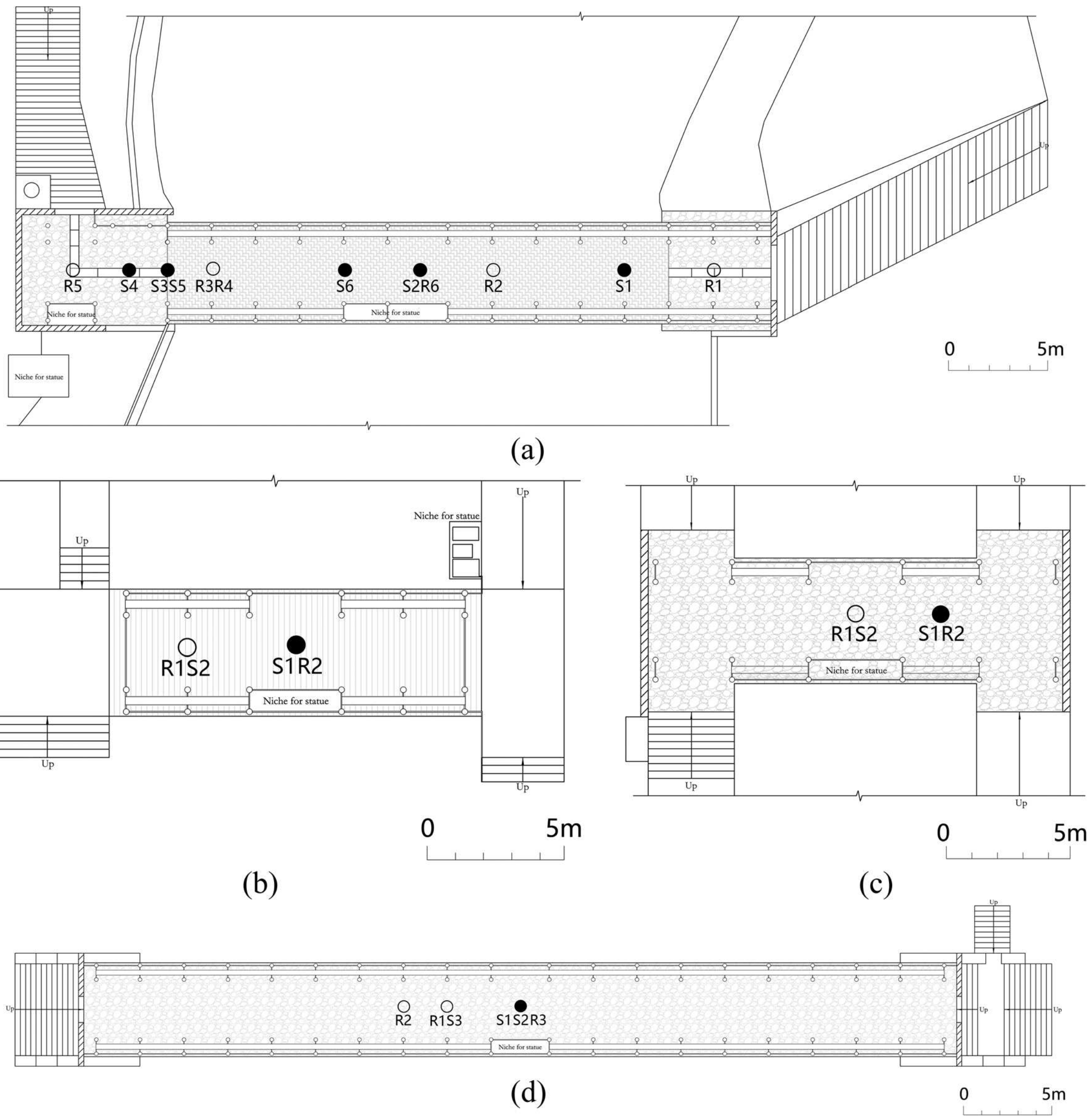

FIG. 4. Plan views of the four CITAC bridges under study, showing the positions of the sound sources and acoustic receivers: (a) Denglong Bridge, (b) Shuangmen Bridge, (c) Futian Bridge, and (d) Lanxi Bridge.

approximate their acoustic influence. This simplified approach and the setting of the acoustic parameters of the complex elements were also based on the results of previous studies by this research team (Zhang *et al.*, 2023; Zhang *et al.*, 2020a; Zhang *et al.*, 2020b). Table II lists the sound absorption and scattering coefficients of various indoor materials, which were determined via the above method.

The reverberation times for the six frequency bands (125 to 4 kHz) of the four CITAC bridges were calculated via Odeon. Figure 6 shows that the percentage differences between the T30 values (the ratio of the difference between the simulated and measured values to the measured value) were mostly between −20% and 20% and from −10% to 10% for the middle-frequency and high-frequency data. In general, the errors were lower for middle and high frequencies than for low frequencies, which is a limitation of this type of acoustic modeling approach (Wang and Kang, 2022). International acoustic standards require that simulation errors be less than the just noticeable difference (JND) for the parameter, which is 5% for the reverberation time. However, the studied CITAC bridges are not fully enclosed, with varying degrees of openings along both the long and short axes. Although Odeon is capable of simulating semi-open spaces, when some bridge openings are close to or smaller than the wavelength of sound, the reflection and propagation paths of sound waves are affected. This can reduce the accuracy of sound field simulations via ray-tracing methods, which may lead to differences between measured and simulated values that exceed the JND. Considering that the subsequent analysis of the simulation results in this study focused mainly on the middle- and high-frequency ranges and that the objective was to investigate the influence of various factors on the sound fields of the

FIG. 5. Sound source in the CITAC bridge.

CITAC bridges and the relative variations in different acoustic parameters, the differences between the simulated and measured values were considered within an acceptable range.

C. Building a standard acoustic model of the CITAC bridge

On the basis of our site survey and previous research on CITAC bridges in Fujian and Zhejiang Provinces (Xiao *et al.*, 2020), most CITAC bridges have widths ranging from 4–6 m and lengths ranging from 10–60 m. Among these, small bridges typically have lengths ranging from 10–20 m, medium-sized bridges have lengths ranging from 20–40 m, and large bridges generally have lengths exceeding 40 m. The Wanan Bridge in Fujian Province, with a length of 98.2 m, is the longest surviving CITAC bridge in China (Tang, 2010). The spans of CITAC bridges are typically singular, with the middle span being the largest, approximately 3–3.5 m in length, and symmetrical on both sides of the center. The entrance styles of CITAC bridges can be classified into three main categories: direct entry (without gable walls), side entry (with complete gable walls), and direct entry through gable walls (gable walls with openings). In this study, the standard acoustic model of the CITAC bridge was based mainly on large bridges that frequently host various ritual activities. The standard acoustic model was set with a length of 48 m, a width of 5 m, a height of 4.3 m, and 17 spans (Fig. 7), with an aspect ratio close to the average of the 99 surveyed CITAC bridges.

TABLE II. Sound absorption and scattering coefficients of materials in the acoustic model (adjusted to match the measured results).

Material	Sound absorption coefficient at different frequencies (Hz)						
	125	250	500	1 kHz	2 kHz	4 kHz	Scattering coefficient
Stone steps	0.01	0.01	0.02	0.02	0.02	0.05	0.25
Wooden beams	0.19	0.43	0.44	0.40	0.42	0.40	0.30
Roof	0.25	0.40	0.50	0.55	0.60	0.60	0.50
Plain brick wall	0.05	0.04	0.02	0.04	0.05	0.05	0.06
Niche for a statue	0.10	0.07	0.05	0.05	0.05	0.05	0.50
Wooden wall	0.16	0.15	0.10	0.10	0.10	0.10	0.35
Bucket arc	0.25	0.30	0.40	0.50	0.50	0.50	0.30
Wooden eave columns	0.10	0.07	0.05	0.05	0.05	0.05	0.40
Hard floor paving	0.01	0.01	0.02	0.02	0.02	0.05	0.15
Wooden paving	0.01	0.01	0.02	0.02	0.02	0.05	0.05
Indoor hardwood material	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Glazed window	0.35	0.25	0.18	0.12	0.07	0.04	0.02
Lanterns	0.03	0.04	0.11	0.17	0.24	0.35	0.35
Grassland	0.11	0.26	0.60	0.69	0.92	0.99	0.60
Plastered brick wall	0.03	0.03	0.03	0.04	0.05	0.07	0.05
Light textile cushion	0.33	0.55	0.64	0.58	0.61	0.58	0.20
Wooden ceiling	0.16	0.15	0.10	0.10	0.10	0.10	0.40
Bluestone ground (small)	0.01	0.01	0.02	0.02	0.02	0.03	0.15
Bluestone ground (big)	0.01	0.01	0.02	0.02	0.02	0.05	0.40
Mud	0.15	0.25	0.40	0.55	0.60	0.60	0.60

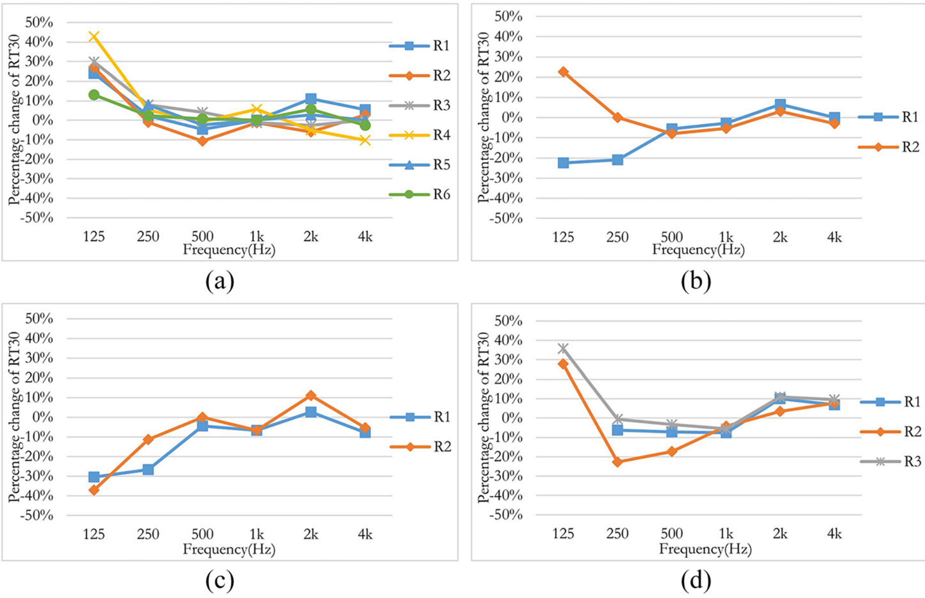

FIG. 6. Percentage differences in reverberation time between the measured and simulated results for the four CITAC bridges (R1–R6 refer to the acoustic receivers inside the CITAC bridges, with their locations shown in Fig. 4): (a) Denglong Bridge, (b) Shuangmen Bridge, (c) Futian Bridge, and (d) Lanxi Bridge.

The entrance style of the standard acoustic model was set as the side entry type. A niche for a statue was placed in the central span, and the overall interior layout and the enclosure structure systems were consistent with the most common configurations of large CITAC bridges. The lower part of the exterior wooden walls housed railings and wooden benches, whereas the upper part included semi-open protective wooden panels with small windows.

The indoor spaces of CITAC bridges can be regarded as both performance spaces and religious spaces during ritual activities. On the basis of previous observations of ritual activities performed on such bridges, as shown in Fig. 8, the sound source was placed in front of the statue niche at the center of the standard acoustic model. Three acoustic receivers were placed symmetrically on either side of the center. The average results from three receivers were used to determine the parameter values for the sound fields of the CITAC bridges. Considering the symmetrical nature of the bridges, the acoustic receivers were arranged on only one side of each bridge. In accordance with acoustic measurement standards and the actual conditions of ritual activities, the sound sources and receivers were both set 1.5 m above the floor. Notably, the input parameters for the sound sources were the sound power levels for each frequency band, as required by the acoustic simulation software. However, religious ceremonies held on CITAC bridges typically involve multiple simultaneous sound sources, such as chanting and ritual instruments, making it difficult to distinguish and simulate each source individually. In this study, to simplify the sound field simulation of the CITAC bridges, only one sound source was placed at the central location of ritual activities in the bridge acoustic model. The input parameters of this sound source were derived from the sound pressure levels in each frequency band recorded by this research team during previous similar religious celebrations via a high-fidelity recorder. This recording scenario also involved multiple spatially dispersed and simultaneous sound sources, and the recorder was positioned at the center of the

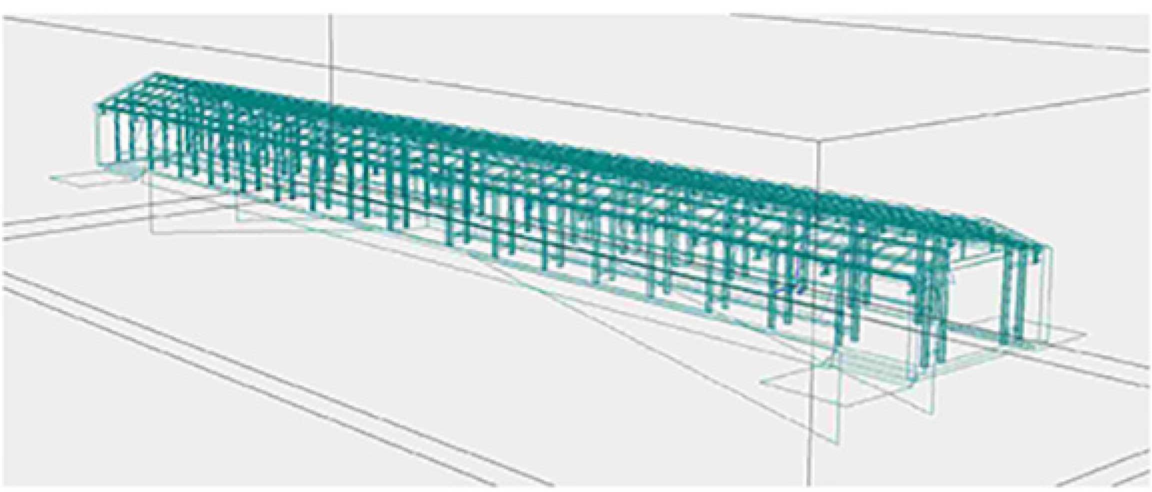

FIG. 7. Perspective view of a standard acoustic model of the CITAC bridge.

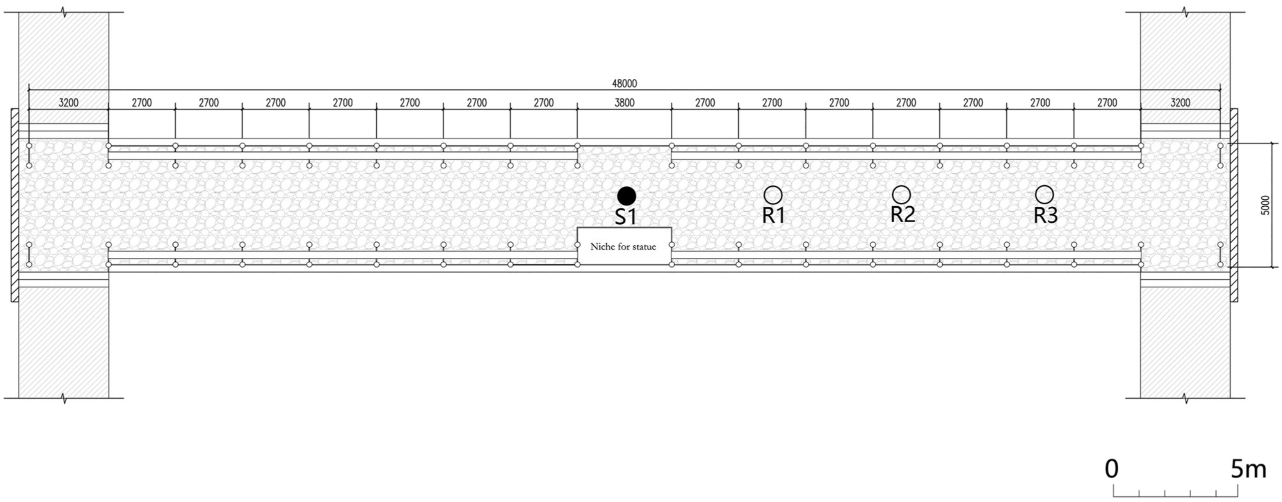

FIG. 8. Floor plan of the standard acoustic model of the CITAC bridge and layout of the sound sources and receivers.

ritual activity area, with a distance of more than 1 m from each source (Zhang *et al.*, 2020b). The recorded sound pressure levels for the six frequency bands (125 to 4 kHz) were 54.1, 55.7, 56.4, 47.8, 39.5, and 34.9 dB. More importantly, the simulated acoustic parameters of the CITAC bridges in this study, including the SPL, RT_{30}, and the speech transmission index (STI), were analyzed on the basis of their relative variations and trends. Therefore, in order to keep the input values within a reasonable range and avoid obvious deviation from the realistic conditions, it was acceptable to use these measured sound pressure levels as the sound power levels for each frequency band in the simulation. The absorption and scattering coefficients of the surface materials used in the standard acoustic model are listed in Table II.

With respect to the acoustic model established in this study, extensive measurements and simulations of traditional Chinese performance spaces were previously conducted by this research group (Zhang *et al.*, 2023; Zhang *et al.*, 2020a; Zhang *et al.*, 2020b); these analyses involved buildings with materials and spatial characteristics similar to those of CITAC bridges. The acoustic parameters of traditional Chinese building materials suitable for simulation in Odeon software were obtained in these studies. Owing to the limitations of onsite measurement conditions, the simulation results were validated only against the measured RT_{30} values. However, reverberation time, one of the most critical parameters of the sound field, was measured and used to repeatedly calibrate and validate the acoustic models across four CITAC bridges. This approach ensured adequate simulation accuracy for other reverberation-related parameters, such as early decay time (EDT), STI, and clarity (C80). Moreover, with respect to the accuracy of the simulated SPL values, this study compared the differences in the relative variations in the sound fields of CITAC bridges under different modeling conditions and identified trends in SPL changes. Therefore, the acoustic model established in this study can be considered adequate for sound field simulation and analysis.

Field research on CITAC bridges (Fig. 1) and previous studies developed by this research team on the sound fields of traditional Chinese architecture (Zhang *et al.*, 2023; Zhang *et al.*, 2020b) indicated that the main factors influencing the sound fields of CITAC bridges could be their spatial dimensions and enclosure structure systems, as well as the bridge occupancy status. As shown in Fig. 9, the impact of changes in the following six factors on the standard acoustic model was investigated: (a) length; (b) aspect ratio and cross-sectional area; (c) enclosure structure systems, encompassing the protective wooden panels under the eaves and the gable walls on both sides; (d) ceiling design; (e) paving materials; and (f) bridge occupancy. The mechanisms by which these factors influence the sound field parameters of CITAC bridges were subsequently analyzed.

The background noise level in the simulation was set on the basis of the maximum background noise measured across all the bridges at each frequency band, and the background noise level measured for each bridge was similar. A previous study revealed no significant effects of environmental factors, such as temperature, humidity, or wind, on the sound field characteristics of open-air theaters (Psarras *et al.*, 2013). The environmental settings of this model included a temperature of 20 °C, a humidity of 50%, and a wind speed of 0 m/s. The effects of changes in these factors on the sound field were not considered.

D. Sound field evaluation parameters

In this study, the interior of the CITAC bridges is regarded as a traditional religious performance space on the basis of its functional use. To evaluate the sound field characteristics, several important acoustic parameters from previous research on the sound fields of religious and performance spaces (Mao *et al.*, 2023; Wang and Kang, 2022; Zhang *et al.*, 2024) were considered. The acoustic parameters of the performance space were generally adopted from the Western sound field evaluation index system. Although the architectural forms and types of performances in

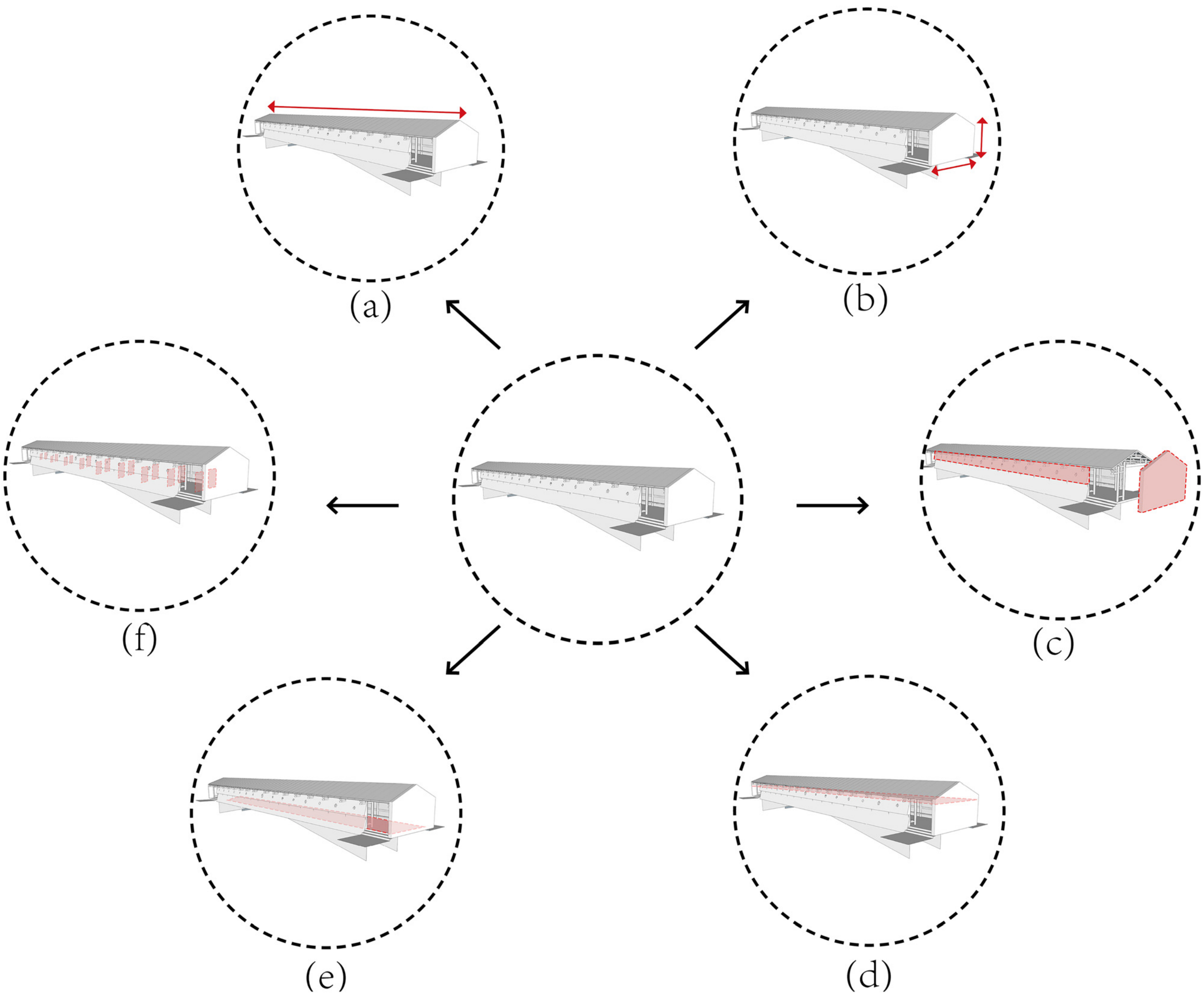

FIG. 9. Scheme of the variables analyzed: (a) length, (b) aspect ratio and cross-sectional area, (c) enclosure structure systems, (d) ceiling design, (e) paving materials, and (f) bridge occupancy.

Chinese and Western theaters differ, this system is often applied in studies of traditional Chinese performance spaces (Chaing *et al.*, 2003; Hsu *et al.*, 2002; Wang, 1999,2014; Zhang *et al.*, 2023), and it is recognized for its representativeness and comprehensiveness in evaluating sound field characteristics. Therefore, the following parameters were selected for analysis: RT_{30}, EDT, the A-weighted sound pressure level [SPL(A)], the inter-aural cross correlation coefficient (IACC), STI, and C80. In addition, some ideal parameter values of Eastern and Western performance spaces were compared. However, owing to differences in architectural conditions, functional requirements, and cultural backgrounds, this comparison was intended only as a general reference rather than a detailed equivalence assessment.

1. Reverberation time

In this study, the representative mid-frequency RT_{30} values (average values of 500 and 1000 Hz, defined as RT_{30M}) were selected as the acoustic parameters of the CITAC bridges for analysis and comparison. Previous research has indicated that the measured reverberation times of typical excellent traditional Chinese drama performance spaces range from 1.00–1.20 s in the octave bands from 500 to 2000 Hz (Wang, 1999), whereas the reverberation time for the best Western concert halls for symphonic music is approximately 2.0 s (Beranek, 2004).

2. Early decay time

The EDT has been recognized as a better measure of subjectively perceived reverberance than reverberation time (Mo and Wang, 2013; Soulodre and Bradley, 1995). In previous studies on the acoustics of Chinese courtyard theaters, it was found that in open or semi-open spaces, EDT is more suitable as a parameter for evaluating reverberation time (Wang, 2007). Other relevant studies have yielded similar conclusions (Peng *et al.*, 2020; Xue and Wang, 2004). In this study, the representative mid-frequency EDT values (average values of 500 and 1000 Hz, defined as EDT_M) were selected as the acoustic parameters of the CITAC bridges for analysis and comparison. Previous research has indicated

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that the EDT_M values in traditional Chinese theaters typically range from 0.83–1.39 s (Peng *et al.*, 2020; Shi *et al.*, 2005; Sun *et al.*, 2011; Zhang *et al.*, 2023; Zhao *et al.*, 2011; Zhu *et al.*, 2013), whereas in the best Western concert halls, the EDT_M values are between 2.25 and 2.75 s (Beranek, 2004).

3. Sound pressure level

The SPL(A) was selected because it is weighted to be a better match for human auditory ability. Typically, under controlled conditions, humans can distinguish a change in SPL of 1 dB, whereas in complex acoustic environments, a change of 3 dB or more is generally considered clearly perceptible or noticeable (Fastl and Zwicker, 2007; Wang and Vigeant, 2004).

4. Speech transmission index

The ritual celebrations and chanting activities held on the CITAC bridges involve a significant amount of language dialog, and the STI is an important parameter for evaluating the sound field quality of a CITAC bridge. The STI is an objective parameter that indicates the quality of speech transmission and is associated with speech intelligibility, with a value ranging from zero to one. Following the international standard, if the STI value is above 0.75, the speech intelligibility rating is "excellent." Values between 0.60 and 0.75 correspond to "good," values between 0.45 and 0.60 correspond to "fair," values between 0.30 and 0.45 correspond to "poor," and values less than 0.30 correspond to "bad" (ISO, 2003).

5. Inter-aural cross correlation coefficient

The IACC indicates the difference in sound that is audible to both ears and can be used to evaluate the spaciousness of sound. The IACC is measured at a position reached by sound within 80 ms after emission, usually expressed as an average over three frequencies (500 Hz and 1 and 2 kHz), and is denoted by $IACC_{E3}$. A study of the acoustic quality of multiple concert halls demonstrated that the value of $(1 - IACC_{E3})$ has a positive correlation with subjective sound evaluation by audiences and is a parameter that can be used as a reference to evaluate the acoustic quality of concert halls (Hidaka *et al.*, 1995). Considering that CITAC bridges also serve as venues for religious music performances, the subjective evaluation methods used in concert halls have certain reference value for assessing the sound field of these bridges. Previous research has indicated that the $(1 - IACC_{E3})$ values in traditional Chinese theaters typically range from 0.610–0.790 (Zhu *et al.*, 2013), whereas in the highest-rated Western concert halls, the $(1 - IACC_{E3})$ values are typically above 0.6 (Beranek, 2004).

6. Clarity

The parameter C80 was used to describe the degree of music clarity and is expressed in dB. Typically, a long reverberation time is associated with a low C80 value and, consequently, a low degree of music clarity. C80 is usually measured as an average of the 500 and 1 kHz octave bands and is denoted by $C80_M$. It cannot be used to evaluate the acoustic quality of a hall, but can indicate whether the music is very clear or whether the reverberation time is extremely long (Martellotta, 2010). In Western concert halls with relatively well-regarded acoustic qualities, the clarity in the vacant state is generally between -1 and -4 dB (Beranek, 2004). Two traditional Chinese indoor theaters widely considered to have superior acoustics are the Shijia Theater auditorium, with a measured $C80_M$ value of 3.1 dB (Shi *et al.*, 2005), and the Beijing Gongwangfu Theater, with a $C80_M$ value of 0.7 dB (Zhu *et al.*, 2013). In addition, preliminary research by this research team revealed that the simulated $C80_M$ values of the Jiayintang Theater and Main Hall of a Han Buddhist temple model are 3.0 and 4.5 dB (Zhang *et al.*, 2023; Zhang *et al.*, 2020b), respectively. This finding indicates that the optimal value range of C80 in traditional Chinese theaters may be greater than that in Western concert halls.

The JND values of the six acoustic parameters from previous studies are listed in Table III (Álvarez-Morales *et al.*, 2014; Christensen and Koutsouris, 2016; D'Orazio *et al.*, 2018; ISO, 2009; Okano, 2002; Wang and Vigeant, 2004). Notably, ISO 3382-1 generally sets the JND for changes in reverberation time at 5%. However, this JND value corresponds to concert and multipurpose halls with a typical RT range of $1.0 - 3.0$ s. Since the field-measured RT_{30} values inside the CITAC bridges are lower than those in such venues, a 5% variation may be insufficient for the human auditory perception of reverberation time. Additionally, previous studies have shown that the JND for reverberation time is often greater than 5% (Blevins *et al.*, 2013). As mentioned above, considering the semi-enclosed nature of the CITAC bridge space, the acceptable difference between the simulated and measured reverberation times is set to be less than 10%. Accordingly, the JND values for RT_{30M} and EDT_M in this study are set to 10% to avoid overestimating perceptual differences when the RT_{30} is small. A change in the sound field characteristics of the CITAC bridges is considered significant when the value meets or exceeds this threshold.

III. RESULTS

The reverberation times of four traditional CITAC bridges located in Fujian and Zhejiang Provinces were measured in this study. On the basis of these measurements, a standard acoustic model was established to characterize the sound field properties of the CITAC bridges. Additionally, the associated factors influencing the bridge sound fields were examined by modifying the spatial dimensions, enclosure structure systems, and occupancy conditions of the bridges within the standard model. This approach was used to explore how these factors specifically affect the sound field characteristics of CITAC bridges.

TABLE III. JND for six evaluation parameters.

Parameter	RT $_{(0.5–1\ kHz)}$	EDT $_{(0.5–1\ kHz)}$	SPL(A)	STI	$IACC_{E3(0.5–2\ kHz)}$	$C80_{M\ (0.5–1\ kHz)}$
JND	10%	10%	3 dB	0.03	0.075	1 dB

A. Sound field characteristics of the interior spaces of CITAC bridges

1. Acoustic field measurement results

The four CITAC bridges—Denglong Bridge in Fujian Province and Shuangmen, Futian, and Lanxi Bridges in Zhejiang Province—differ in terms of their enclosure structures and dimensional ratios. In this study, the reverberation times of these four bridges were tested onsite, and the RT_{30} results obtained from the tests are shown in Table IV. The following conclusions were reached on the basis of the test results:

(1) The measured reverberation times for each bridge generally decreased from middle frequencies to high frequencies, with similar high-frequency reverberation times for the four bridges. The mid-frequency reverberation times (500 and 1000 Hz) of the four bridges ranged from 0.37 to 0.50 s, with an average value of 0.43 s. The high-frequency reverberation times (the average values for 2000 and 4000 Hz) ranged from 0.33 to 0.40 s, with an average value of 0.37 s.

(2) The RT_{30M} of the four bridges can be ordered from longest to shortest as follows: Lanxi Bridge > Futian Bridge > Denglong Bridge > Shuangmen Bridge. The Lanxi Bridge, Futian Bridge, and Denglong Bridge are all equipped with gable walls, whereas Shuangmen bridge features direct entries at both ends and no gable walls. Therefore, it is hypothesized that the presence of gable walls and the entrance styles at both ends of the CITAC bridges may influence the reverberation time.

(3) A comparison of the measured reverberation times at various acoustic receivers inside the bridge revealed that the mid-frequency reverberation time was shorter at the receivers near the niche for the statue and the entrance than at the receiver located between the two. This could be due to the relative enclosure of the central area, where sound signals are reflected multiple times. The window openings at the statue niche in the center of the bridge are the largest, whereas the spaces near the entrances on both sides are more open, contributing to faster sound dissipation in these areas. The simulation results obtained with the standard acoustic model align with the measured results, with the reverberation time at the central receiver (R2) being the longest among the reverberation times at the three acoustic receivers.

2. Acoustic parameters of the standard acoustic model

In this section, Tables V and VI present the simulation results for the standard acoustic model with various acoustic parameters. The simulated average reverberation times (EDT and RT_{30}) closely match the measured results, displaying a generally decreasing trend from middle frequencies to high frequencies. The EDT_M values for the three receivers ranged from 0.53 to 0.58 s, with an average value of 0.55 s. The RT_{30M} values ranged from 0.57 to 0.68 s, with an average value of 0.63 s. The simulated C80 values increased gradually from low to high frequencies. For the three receivers, the $C80_M$ values ranged from 8.3 to 9.1 dB, indicating minimal variation in music clarity at different bridge positions, with an average value of 8.6 dB. The average STI value for the three receivers was 0.45, which was considered "fair" based on ISO 9921 (ISO, 2003). The lowest STI value was observed at receiver R3, which was located farthest from the sound source and near the bridge entrance, where sound dissipates rapidly, reducing speech intelligibility. The SPL(A) simulation results show that the sound pressure level notably decreased with increasing distance from the receiver, with a 6.7 dB difference between receivers R1 and R3, exceeding the JND value. This is likely due to the relatively poor degree of enclosure of the bridge, which results in rapid sound dissipation. The $IACC_{E3}$ simulation results indicate that the $(1 - IACC_{E3})$ value of R3 was lower than that of the receivers at the center of the bridge (R1 and R2), suggesting greater spaciousness of sound at the center.

B. Factors influencing the internal sound fields of CITAC bridges

In this study, simulations were conducted considering spatial dimensions, enclosure structure systems, and bridge occupancy status to identify the specific effects of various factors on the sound fields of CITAC bridges. As simulations with different paving materials revealed that their

TABLE IV. Average values of the measured RT_{30} at each point in the CITAC bridges by octave bands.

Frequency	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	Mid -frequency
Denglong Bridge	0.38	0.40	0.42	0.39	0.38	0.37	0.41
Shuangmen Bridge	0.40	0.39	0.37	0.36	0.32	0.33	0.37
Futian Bridge	0.77	0.57	0.45	0.45	0.37	0.38	0.45
Lanxi Bridge	0.40	0.57	0.52	0.48	0.41	0.39	0.50

TABLE V. EDT, reverberation time, and C80 simulation results averaged across three receiver locations at six frequency bands for the standard acoustic model.

Frequency	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	Mid -frequency
EDT	0.71	0.61	0.57	0.53	0.51	0.48	0.55
RT_{30}	0.74	0.69	0.66	0.61	0.58	0.52	0.63
C80	5.6	7.4	8.2	9.0	9.5	10.3	8.6

TABLE VI. STI, SPL(A), and $IACC_{E3}$ simulation results at each receiver for the standard acoustic model and their average values.

Acoustic receivers	R1	R2	R3	Average value
STI	0.52	0.44	0.39	0.45
SPL(A)	37.0	33.3	30.3	33.5
$IACC_{E3}$	0.342	0.316	0.512	0.390

influence on the acoustic parameters of CITAC bridges did not exceed the JND values in the vast majority of cases, this factor is not further discussed. The simulation results for each factor are shown in Table VII.

1. Spatial dimensions

a. Length. In this study, the standard acoustic model was set to a total length of 48 m. The sound field simulation results indicated that, with the aspect ratio and cross-sectional form held constant, varying the bridge length to 70%, 130%, and 160% of the standard length (100%) resulted in RT_{30M} values increasing by −13.98%, 18.47%, and 52.77%, respectively, whereas the EDT_M values demonstrated minimal variation, with increases of −2.74%, 2.43%, and 5.47% respectively. Under the same conditions, the STI values decreased by −0.04, 0.05, and 0.09, whereas $C80_M$ and SPL(A) decreased by only 1.4 and 4.83 dB, respectively, at 160% of the standard length; the other changes did not exceed the corresponding JND values. The $IACC_{E3}$ variation was smaller than the JND value.

b. Aspect ratio (height-to-width). The impact of the aspect ratio of the cross-section on the sound fields of the CITAC bridges was subsequently analyzed. When the cross-sectional area (19 m^2) remained unchanged, the aspect ratio of the cross section was varied from 0.86:1 for the standard acoustic model to 1:1, 1:0.86, and 1:0.7. The average EDT_M value at each point along the CITAC bridges in the simulations increased by 2.13%, 6.08%, and 10.03%, respectively, indicating that increasing the aspect ratio leads to an increase in EDT_M. In terms of the other acoustic parameters, the RT_{30M} value increased by −4.49%, 3.17%, and −5.80%, but these changes did not exceed the JND values, and there was no obvious change trend. The $C80_M$ value decreased by 1.3 dB only when the aspect ratio was 1:0.7, whereas the other changes did not exceed the corresponding JND values. Furthermore, the changes in the STI, $IACC_{E3}$, and SPL(A) values did not exceed the corresponding JND values. As shown in Fig. 10, when different aspect ratios were simulated, the reverberation time at the receiver near the end of the bridge (R3) varied more than that at the receiver near the center of the bridge (R1).

c. Cross-sectional area. In the next analysis, the aspect ratio of the cross-section of the CITAC bridge (0.86:1) remained unchanged, and the sound field was simulated when the cross-sectional area of the standard acoustic model (19 m^2) was changed to 80%, 120%, and 140% of the standard value. The results revealed that the EDT_M value increased by −8.81%, 4.86%, and 11.25%, respectively; the RT_{30M} value increased by −7.39%, 4.49%, and 10.29%, respectively; and $C80_M$ increased by 1.1, −0.4, and −1.2 dB, respectively. The STI, $IACC_{E3}$, and SPL(A) values remained essentially constant.

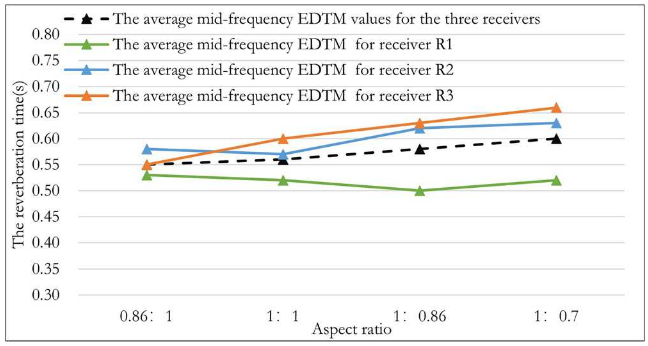

FIG. 10. The effect of changes in the aspect ratio on the EDT_M.

d. Relationship between volume and reverberation time. A simulation study of the spatial dimensions of the CITAC bridge revealed that as the volume of the bridge (length and cross-sectional area) increases, the reverberation time increases. Figure 11 shows the reverberation times of small Eastern and Western performance spaces and religious spaces with volumes similar to those of the CITAC bridges. On the basis of this model, linear regression was performed between the volume and reverberation time, and the fitting formula was as follows:

$$Y = 0.000145257X + 0.577764, \quad (1)$$

where Y is the mid-frequency reverberation time, measured in seconds (s), and X is the volume of the space, measured in cubic meters (m^3).

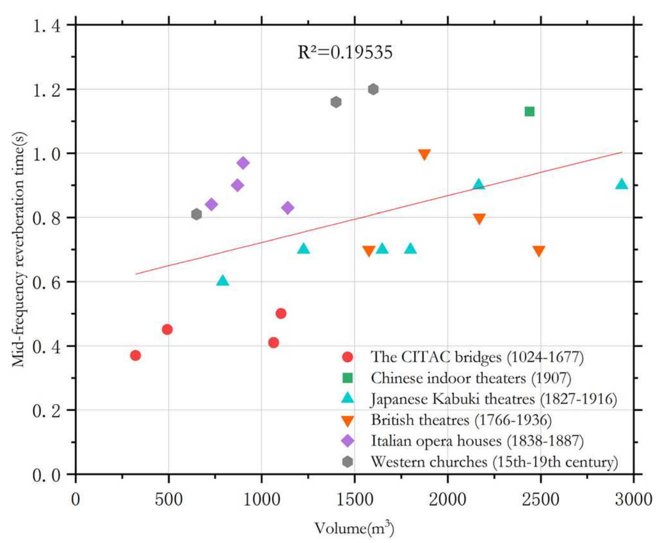

FIG. 11. Relationship between the volume of different performance and religious spaces and their RT_{30M} values on the basis of measurements.

The above formula is similar to the Sabine equation, indicating a directly proportional relationship between reverberation time and volume. However, considering that the R^2 value is only 0.19535, this suggests that, in addition to volume, other factors, such as materials, spatial form, and degree of enclosure, may affect the reverberation time in such spaces. The fitted line may not accurately represent a strong correlation due to the scattered nature of the data and the differences in functional use and construction materials. It should be noted that, in this study, the purpose of including linear regression was to illustrate the general relationship between volume and reverberation time across different traditional performance spaces and to facilitate comparisons among different types of performance spaces rather than to propose a precise predictive model.

2. Enclosure structure systems

The enclosure structure systems of CITAC bridges typically include protective wooden panels along the longitudinal axis, brick gable walls along the transverse axis, roofs, and paving materials.

a. Protective wooden panels. Protective wooden panels usually open outward at an angle (Fig. 12); therefore, a standard acoustic model was established to simulate sound fields with protective wooden panels set at opening angles of 0°, 15°, 30°, and 45°, as well as a case in which the panels were removed. The longest EDT_M value was 0.55 s at an opening angle of 15°, which was only 0.02 s longer than the EDT_M value at an opening angle of 0°. From an opening angle of 15°, the EDT_M value decreases by approximately 10% for each 15° increase in the opening angle. Compared with that for panels at a 15° angle, the EDT_M value was reduced by 26.14% when the protective wooden panels were removed. These results indicate that the opening angle of the protective wooden panels significantly influences the interior sound field. Field investigations revealed that the opening angle of protective wooden panels is approximately 15° for most traditional CITAC bridges. This approach likely provides several benefits, such as improved air circulation and protection for wooden walls and foundations from rainwater damage. This angle also ensures a greater degree of enclosure while minimizing sound energy loss. Furthermore, owing to the relatively small scale and semi-open nature of the CITAC bridge space, the reverberation time is significantly shorter than the mid-frequency reverberation time of 1.00–1.20 s in traditional Chinese performance buildings with good acoustic quality, as discussed earlier. However, the protective wooden panels increase the reverberation time, allowing the sound field within the bridge to better meet the needs of attendees of ritual activities and improve the overall quality of the acoustic environment during these events. In terms of the other acoustic parameters, compared with those of bridges with protective wooden panels with an opening angle of 15°, the changes in the RT_{30M} and $IACC_{E3}$ values of CITAC bridges with angles of 0°, 30°, and 45° did not exceed the corresponding JND values. However, after removing the protective wooden panels, the RT_{30M} value increased by 22.43%, and the $IACC_{E3}$ value increased from 0.390 to 0.527, a difference of 0.137, both of which exceeded the corresponding JND values. Compared with the $C80_M$ value of 8.6 dB for the bridge with a 15° protective wooden panel, the $C80_M$ value increased by 0.3, 1.3, and 2.8 dB at angles of 0°, 30°, and 45°, respectively, and by 3.8 dB after the panels were removed. Except in the 0° angle case, these changes exceeded the JND value. The changes in the STI and SPL (A), however, were smaller than the JND values. Overall, the impact of protective wooden panels on the acoustic parameters is reflected primarily in the EDT_M and $C80_M$ values, whereas the changes in the other parameters were relatively small. The previous simulations indicated that the change trend of RT_{30M} differs from that of EDT_M as the opening angle of protective wooden panels increases. To analyze this phenomenon, sound field simulations were conducted in this study via the standard acoustic model without gable walls at both ends. As shown in Fig. 13, starting from 15°, every 15° increase in the opening angle led to an approximately 12% decrease in the EDT_M value

FIG. 12. Protective wooden panels.

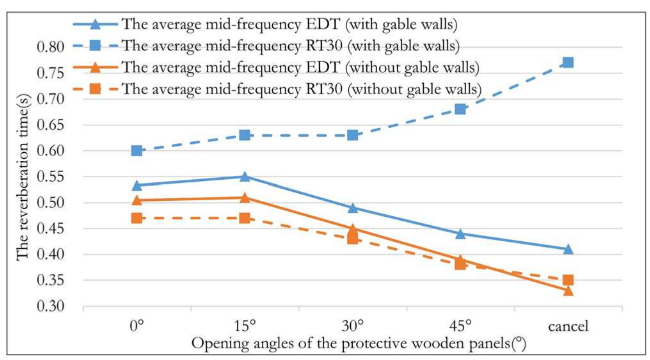

FIG. 13. The effects of the opening angles of the protective wooden panels on the EDTM and RT30M.

and a 9.5% decrease in the RT_{30M} value of the CITAC bridge. When the protective wooden panels were removed, the EDT_M value decreased by 34.85%, and the RT_{30M} value decreased by 25.53% compared with those of the bridge with the panels at an opening angle of 15°, with both parameters exhibiting consistent trends. These results suggest that the presence of gable walls may have a unique influence on the RT_{30M} values of CITAC bridges.

Additionally, various window-to-wall ratios for the protective wooden panels were simulated to investigate their effects on the sound field of the CITAC bridges. When the ratio was increased from 0.03:1 in the standard acoustic model to 0.12:1 (four times larger) or when the windows were completely removed, all the changes in the acoustic parameters remained below their JND values. Therefore, these results suggest that windows provide ventilation, lighting, and viewing functions and allow external natural sounds such as flowing water and bird calls to be heard on the bridges while having minimal impact on the internal sound field.

b. Gable walls. The measured results at the four CITAC bridges demonstrated that the gable walls at both ends and the entrance styles may affect the reverberation time inside the bridges. Three acoustic models with the same length and cross-sectional area but different entrance styles were established to analyze the specific effects of gable walls on the indoor sound field. The simulation results indicated that the longest RT_{30M} value was achieved with the standard acoustic model with a side entry style with complete gable walls. When the entrance style was changed to direct entry (without gable walls) or direct entry through gable walls (gable walls with openings), the RT_{30M} values decreased by 25.59% and 22.69%, respectively, which were significantly greater than the JND values for the reverberation time. In contrast, the EDT_M values decreased by 6.69% and 2.43%, respectively, which were not significant. The changes in the $C80_M$, STI, $IACC_{E3}$, and SPL(A) values were all below their respective JND values. This further confirmed that the gable walls and entrance styles have the most significant impacts on RT_{30M} among the acoustic parameters.

c. Suspended ceiling. In traditional Chinese architecture, there are two types of interior roofs. The first type features a wooden flat suspended ceiling, which is relatively smooth because of the painting and decoration. The second type lacks a suspended ceiling, which exposes the structural elements of the roof, such as beams and purlins. Most existing CITAC bridges lack a suspended ceiling. To analyze the effect of adding a suspended ceiling on the sound field of CITAC bridges, a new acoustic model was established. The planar form, source and receiver positions, absorption coefficients, and scattering coefficients of this model were the same as those in the standard acoustic model, and a flat wooden suspended ceiling was added. The simulation results revealed that when the suspended ceiling was added, the EDT_M and RT_{30M} values increased by 82.98% and 46.44%, respectively. Moreover, SPL(A) increased by 6.2 dB, $C80_M$ decreased by 4.0 dB, the STI value increased by 0.05, and $IACC_{E3}$ decreased by 0.097. The results indicate that the wooden flat ceiling significantly affects the sound fields of CITAC bridges. The addition of a flat wooden ceiling to the CITAC bridge resulted in increased reverberation time, SPL(A), and STI values and decreased values of $C80_M$ and $IACC_{E3}$.

3. Bridge occupancy

The previous measurements and simulations were conducted with an unoccupied bridge. To investigate the effect of occupancy on the sound fields of CITAC bridges during ritual activities, human models were added to the standard acoustic model, with sound absorption coefficients set according to previous research (Chagok *et al.*, 2013). Observations of actual ritual activities indicated that each span of the CITAC bridge could accommodate up to approximately 8 participants (with an average area of approximately 1.6 m^2 per person), representing 100% occupancy. In cases with 6, 4, and 2 participants, the occupation ratios were 75%, 50%, and 25%, respectively, whereas the standard acoustic model (unoccupied condition) was regarded as 0% occupation. As shown in Fig. 14, compared with those for the standard unoccupied acoustic model, the EDT_M value decreased by 9.42%, 15.20%, 17.63%, and 20.97%, respectively; the RT_{30M} value decreased by 7.92%, 14.49%, 21.37%, and 22.69%, respectively; the SPL(A) value decreased by 1.9, 3.4, 3.9, and 4.5 dB; the STI value decreased by 0.03, 0.05, 0.06, and 0.06, respectively; the $(1 - IACC_{E3})$ value decreased by 0.046, 0.088, 0.144, and 0.139, respectively; and the $C80_M$ value increased by 2.3, 3.1, 5.0, and 5.7 dB, respectively, as the occupancy increased to 25%, 50%, 75%, and 100% in the new model. These results indicate that increasing the number of participants reduced RT_{30M}, EDT_M, STI, and SPL, negatively affecting sound spaciousness. However, higher occupancy improved music clarity.

On the basis of the simulation studies, the results for the six evaluation parameters affecting the sound fields of

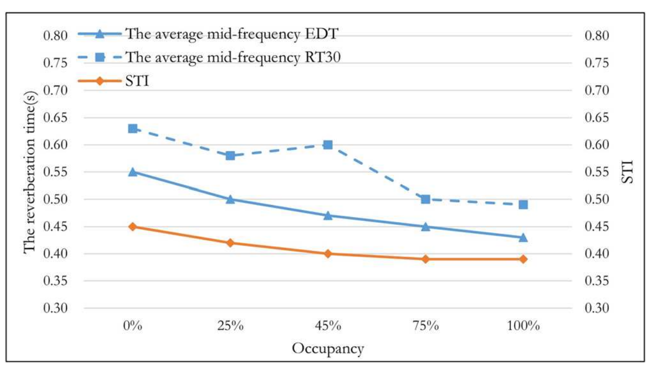

FIG. 14. The effect of occupancy on EDT_M and RT_{30M}.

TABLE VII. Simulation results for various parameters of the CITAC bridges. The red numbers indicate that the variations in the acoustic parameters exceed the respective JND values.

Changing part	Part	EDT_M (s)	RT_{30M} (s)	SPL(A) (dB)	STI	$IACC_{E3}$	$C80_M$ (dB)
Existing model	Length: 100% Aspect ratio: 0.86:1 Cross-sectional area: 100% Opening angle:15° Entrance styles: side entry Ceiling: without Paving material:0.15[a] Occupancy: 0%	0.55	0.63	33.5	0.45	0.390	8.6
Length	70%	0.53	0.54	35.4	0.49	0.343	8.8
	130%	0.56	0.75	31.1	0.40	0.426	8.4
	160%	0.58	0.97	28.7	0.36	0.440	7.2
Aspect ratio	1:1	0.56	0.60	34.0	0.46	0.370	8.3
	1:0.86	0.58	0.65	33.9	0.46	0.355	7.7
	1:0.7	0.60	0.60	34.1	0.46	0.319	7.3
Cross-sectional area	80%	0.50	0.59	33.4	0.46	0.331	9.7
	120%	0.58	0.66	33.7	0.45	0.401	8.2
	140%	0.61	0.70	33.6	0.44	0.333	7.4
Opening angle	0°	0.53	0.60	33.5	0.44	0.410	8.9
	30°	0.49	0.63	33.0	0.45	0.388	9.9
	45°	0.44	0.68	32.1	0.45	0.456	11.4
	Panels removed	0.41	0.77	31.1	0.44	0.527	12.4
Entrance style	Direct entry	0.51	0.47	33.3	0.45	0.383	9.3
	Direct entry through gable walls	0.54	0.49	33.4	0.45	0.364	8.9
Ceiling	With	1.00	0.93	39.7	0.50	0.293	2.6
Paving material[a]	0.05	0.55	0.59	33.6	0.46	0.388	8.6
	0.30	0.50	0.59	33.2	0.45	0.298	9.5
	0.60	0.50	0.55	33.0	0.45	0.370	9.5
Occupancy	25%	0.50	0.58	31.6	0.42	0.436	10.9
	50%	0.47	0.60	30.1	0.40	0.478	11.7
	75%	0.45	0.50	29.6	0.39	0.534	13.6
	100%	0.43	0.49	29.0	0.39	0.529	14.3

[a]The paving material column in the table gives the corresponding sound absorption coefficient, with values of 0.05, 0.30 and 0.60 in the proposed model.

the CITAC bridges, considering various factors, are summarized in Table VII. The table shows that the addition of a suspended ceiling and occupancy has the greatest impact on the acoustic parameters of the CITAC bridges.

IV. DISCUSSION

A. Comparison with sound fields in similar spaces

CITAC bridges are important examples of traditional architecture in southern China, and the acoustic quality of CITAC bridges has a significant effect on the daily worship and ritual activities of residents. As traditional religious performance spaces, CITAC bridges have functions similar to those of other traditional Eastern and Western performance and religious spaces. Furthermore, the internal spaces of CITAC bridges meet the standard definition of long spaces. By comparing the acoustic parameters of various Eastern and Western performance and religious spaces, as well as the variation patterns of these parameters in typical long spaces, a comprehensive understanding of the sound field characteristics of CITAC bridges can be attained.

1. Comparison with the sound fields of traditional Eastern and Western performance spaces

Table VIII lists the acoustic parameters of Eastern and Western performance spaces obtained in previous studies (Alvarez-Morales and Martellotta, 2015; Barron, 2010; Beranek, 2004; Büttner *et al.*, 2019; D'Orazio and Nannini, 2019; Kosała and Małecki, 2018; Małecki, 2023; Peng *et al.*, 2020; Shi *et al.*, 2005; Sun *et al.*, 2011; Zhang *et al.*, 2023; Zhao *et al.*, 2011; Zhu *et al.*, 2013), including theaters and spaces for religious activities. In this study, the sound field characteristics of these performance spaces were analyzed and compared with those of CITAC bridges.

a. Comparison of acoustic parameters. With respect to the reverberation time, in traditional Eastern performance spaces, as shown in Table VIII, the EDT_M values of Chinese indoor theaters ranged from 0.99 to 1.39 s, with an average value of 1.20 s. The RT_{30M} value ranged from 0.94 to 1.23 s, with an average value of 1.10 s. The EDT_M values of the Chinese courtyard theaters ranged from 0.83 to 1.17 s, with an average value of 0.96 s. As mentioned above, the measured reverberation times of typical excellent traditional

TABLE VIII. Acoustic parameters of Eastern and Western performance spaces and Western churches.

Category	Buildings	EDT_M (s)	RT_{30M} (s)	STI	$IACC_{E3}$	$C80_M$(dB)
Existing model	CITAC bridges	0.55	0.63	0.45	0.390	8.6
Eastern traditional performance space	Chinese indoor theaters	0.99–1.39	0.94–1.23		0.210–0.390	0.7–3.2
	Chinese courtyard theaters	0.83–1.17		0.59		2.4–5.4
	Japanese traditional theaters	0.50–0.90	0.60–1.00	0.62–0.73		
Large Western performance spaces	European concert halls	2.62–3.03	2.00–3.06		0.370–0.485	
	European opera houses	1.16–1.62	1.22–1.75		0.380–0.497	
Small Western performance spaces	Italian opera houses	0.83–1.07				
	British theaters	0.70–1.00				
Western churches	Large Western churches	3.28–10.23	3.29–10.66	0.48–0.49		
	Small Western churches	0.80–1.75	0.81–1.72	0.62–0.70		

Chinese drama performance spaces range from 1.00 to 1.20 s in the octave bands from 500 to 2000 Hz (Wang, 1999). In contrast, the measured mid-frequency reverberation time of the CITAC bridges was significantly shorter, ranging from 0.37 to 0.50 s. Although these performance spaces and CITAC bridges have similar functions, a possible explanation for this difference could be that the internal volume of the CITAC bridges is considerably smaller than that of various theater buildings. For example, the volume of the Guangdong Theater in Tianjin, a Chinese indoor theater, is approximately 2,440 m^3 (Sun *et al.*, 2011), whereas the volume of the CITAC bridges is approximately 1,100 m^3. The Kabuki theater "Playhouse" in Japan, which is also a wooden structure, has poor enclosure characteristics like those of CITAC bridges. Therefore, previous studies have indicated that the EDT_M values of eight Japanese Kabuki theaters are short, ranging from 0.50 to 0.90 s (Büttner *et al.*, 2019; Suzuki and Li, 2009).

In this study, the reverberation times of the CITAC bridges were also compared with those of traditional Western performance spaces and religious spaces. According to Table VIII, compared with those of Western concert halls (average RT_{30M} of 2.86 s), opera houses (average RT_{30M} of 1.45 s), and large churches (average RT_{30M} of 6.12 s), the reverberation times of the CITAC bridges are significantly shorter, mainly due to differences in their volumes. For small Western theaters and churches with volumes similar to those of the CITAC bridges (1100 m^3), one study indicated that the EDT_M of five small Italian opera houses from the 19th century (630–1140 m^3) ranged from 0.83 to 1.07 s, with an average value of 0.92 s. Another study revealed that the EDT_M of four small theaters in the UK (1576–2490 m^3) typically ranged from 0.70–1.00 s, with an average value of 0.80 s. The reverberation times of concert halls and opera houses usually differ, possibly due to the different designs to accommodate different performance types. Additionally, research has indicated that the EDT_M values of small Western churches range from 0.80 to 1.75 s, with an average value of 1.21 s, whereas the RT_{30M} values range from 0.81 to 1.72 s, with an average value of 1.23 s. Although their volumes are similar, the reverberation times of these traditional Western performance spaces and churches are approximately more than twice those of the CITAC bridges. Therefore, in addition to differences in volume, the variations in reverberation times are related to the enclosure characteristics and material differences between the two types of buildings. Furthermore, traditional Western performance spaces and churches are typically enclosed spaces, and the interface surfaces of these spaces are often constructed from hard materials with low absorption coefficients, such as marble, painted concrete, and glass, resulting in significantly greater reverberation times than those of the CITAC bridges.

As shown in Table VIII, the $C80_M$ values of traditional Chinese indoor and courtyard theaters ranged from 0.7 to 5.4 dB, with an average value of 2.9 dB, which is lower than the $C80_M$ value of the standard acoustic model (8.6 dB). This difference may be because activities performed on CITAC bridges, such as prayers and collective chanting by believers, require greater music clarity than do those performed in theaters, which are primarily used for traditional dramatic performances. In terms of the IACC value, in a previous study by this research team, the sound fields of the main halls in traditional Chinese Buddhist temples were simulated on the basis of measurements, yielding a $(1-IACC_{E3})$ value of 0.648 (Zhang *et al.*, 2020b). This value is close to the $(1-IACC_{E3})$ value obtained with the standard acoustic model (0.610) and the average $(1-IACC_{E3})$ value for Chinese indoor theaters (0.680). This similarity may stem from the shared characteristics of traditional Chinese architecture, such as building materials, the locations of sound sources, and the effects of complex structures such as columns and roofs, on sound propagation. In a prior study, 34 Western concert halls were classified as having different quality levels on the basis of their objective acoustic parameters and subjective audience evaluations (Beranek, 2004), revealing that first-tier theaters had $(1-IACC_{E3})$ values ranging from 0.620 to 0.710, second-tier theaters had $(1-IACC_{E3})$ values ranging from 0.460 to 0.610, and third-tier theaters had $(1-IACC_{E3})$ values ranging from 0.410 to 0.440. The $(1-IACC_{E3})$ value of the standard acoustic model was 0.610, indicating relatively good sound spaciousness. In terms of the STI value, the STI values of eight Japanese Kabuki theaters ranged from 0.62 to 0.73. Previous research suggested that optimal speech intelligibility was prioritized in the acoustic design of

Kabuki theaters (Büttner *et al.*, 2019), resulting in reverberation times similar to those of CITAC bridges but with higher speech intelligibility (the standard acoustic model of the CITAC bridges yielded an STI value of 0.45). Additionally, the STI values of Western small churches range from 0.62 to 0.70 (Małecki, 2023), with greater reverberation times and speech intelligibility than those of the CITAC bridges. The results of this study suggest that the low STI values of the CITAC bridges are related to their comparatively low degree of enclosure.

b. Comparison of the factors influencing the sound field. In terms of spatial dimensions, one study on the interior sound fields of traditional wooden Dong Drum tower buildings in China compared two drum towers with similar planar forms and elevation enclosures but different aspect ratios. The results revealed that the overall EDT of a drum tower with a large aspect ratio was slightly longer than that of a drum tower with a small aspect ratio (Mao *et al.*, 2023). Another study, through simulation tests of 25 churches (Berardi, 2014), revealed that the cross-sectional area significantly affects C80. The simulation results revealed a significant increase in C80 with increasing room cross-sectional width (increased cross-sectional area). These previous findings are similar to the simulated results for the CITAC bridges, as increasing the aspect ratio and cross-sectional area led to an increase in the indoor EDT_M value and a decrease in $C80_M$.

In terms of enclosure structure systems, studies on traditional Chinese courtyard theaters (He and Kang, 2010; Wang, 2014; Xue and Wang, 2004; Zhang *et al.*, 2023) have revealed that the higher the degree of enclosure is, the longer the reverberation time and the lower $C80_M$. This finding is generally consistent with the results of the present study on the enclosure structure systems of CITAC bridges. Specifically, as the opening angle of the protective wooden panels increases (indicating a reduced degree of enclosure), the EDT_M value decreases, whereas the $C80_M$ value increases. Furthermore, an analysis of whether the addition of a suspended ceiling affected the interior sound fields of traditional Chinese Buddhist temple main halls was previously performed by this research team (Zhang *et al.*, 2020b). The results revealed that if a suspended ceiling was added, the average RT_{30M} and EDT_M values increased. This finding is generally consistent with the findings for the CITAC bridges, as the addition of a smooth, wooden, flat suspended ceiling in traditional Chinese pitched roof buildings may increase the reverberation time of the internal space. A possible reason is that when the roof lacks a flat suspended ceiling, numerous structural elements, such as beams and purlins, are exposed within the pitched roof, and their rough wooden surfaces allow multiple internal reflections of sound within the roof space, thereby increasing sound absorption. As a result, the interior surface of traditional pitched roofs can be regarded as having relatively high sound absorption. This is in line with previous studies, which indicated that hard materials can also have high sound absorption performance (Kuttruff, 1994). In contrast, when a flat suspended ceiling is added, its surface, which is typically finished with smooth materials such as paint, has a low absorption coefficient (Fujiwara and Miyajima, 1992) and a high reflection coefficient. This increases the reflection of sound within the internal space of the bridge below the ceiling, leading to a longer reverberation time. Moreover, the impact of the increased reverberation time associated with increased sound reflection and reduced sound absorption can exceed the impact of the decreased reverberation time caused by the reduced spatial volume. Notably, after the addition of a flat ceiling, not only did the reverberation time increase, but the STI also increased. This result contrasts with the typical trend in indoor spaces, where reverberation time and STI are usually inversely related. The reason may be that the added flat ceiling covers the complex wooden roof structure of the CITAC bridges, enhancing the early reflected sound in the area beneath the ceiling where people are active, thereby improving acoustic parameters such as speech transmission index within the bridge area. These results suggest that installing a suspended ceiling may generally improve the overall sound field quality inside CITAC bridges. However, most existing CITAC bridges lack a suspended ceiling, which may be due to the following factors. Structurally, a structure without a ceiling requires less material, and the lack of a ceiling facilitates the observation of the wear of the bridge structure for maintenance purposes. Spatially, adding a ceiling could make the space feel overly oppressive and not suitable for holding ritual activities. Moreover, ancient scholars liked to write couplets and poems on the beams and columns of bridges as a form of cultural commemoration (Zhou *et al.*, 2011).

In terms of occupancy, a previous study on six churches revealed that, compared with those under unoccupied conditions, the reverberation time decreased by 29.85% and the STI increased by 0.035 under occupied conditions (Desarnaulds *et al.*, 2002). Another study on religious spaces in India revealed that, compared with those under unoccupied conditions, EDT_M decreased by 48.4%, RT_{30M} decreased by 41.09%, and STI increased by 0.10 when a pagoda was occupied (Manohare *et al.*, 2017). The changes in the reverberation times of these spaces under unoccupied and occupied conditions are similar to those simulated for the CITAC bridges in this study. However, the opposite trend was observed for the STI. In the occupied condition, the STI value of the CITAC bridge significantly decreases. The reason for this difference may be that, compared with spacious and large churches, CITAC bridges have smaller spatial volumes and narrower and longer internal spaces. When the CITAC bridge is occupied, the volume of direct sound reaching the receivers significantly decreases, and the absorption and shielding effects of the audience become stronger. Together, these factors collectively lead to a decrease in the STI value of the CITAC bridge. To test this speculation, a new acoustic model with a wider cross section than that of the standard model was established, which reduces the shielding effect of the crowd on the receivers.

Compared with that obtained with standard acoustic model, the STI value of the new acoustic model decreased less under occupied conditions. This finding indicates that the reduced STI value of occupied CITAC bridges compared with that of other religious spaces is caused by the unique spatial form of CITAC bridges.

2. Comparison with the sound fields of typical long spaces

The cross-sectional height of CITAC bridges is much smaller than their length, so they can be considered long spaces. In this study, comparisons were made between the conclusions regarding the end wall (gable wall) form, length, aspect ratio, and cross-sectional area of the CITAC bridges and those reported in previous studies of long spaces. First, increasing the reflective area of the end walls of the CITAC bridge increased its reverberation time. This result is generally consistent with those of previous studies of the reverberation times of long spaces, which revealed that "highly reflective end walls can increase reverberation significantly" (Kang, 1996c).

Second, increasing the distance between the three receiver points and the sound source in the standard acoustic model increased the reverberation time. Therefore, changes in the length of the CITAC bridge significantly affect RT_{30M}, which is consistent with previous predictions for rectangular long enclosure image source models and field measurements in underground parking garages (Jin *et al.*, 2009; Kang, 1996c). Additionally, as the length increases, the STI value of the CITAC bridge decreases, which is consistent with the measured results of three underground stations with long spaces (Nowicka, 2007a).

Third, a comparison of the measurements obtained at three underground stations (Nowicka, 2007a) revealed that underground stations with sound-absorbing ceilings have the shortest reverberation times. This is consistent with the findings of the present study, as the internal roof structure of traditional Chinese buildings is complex. Without a suspended ceiling, the roof can be considered a highly sound-absorbing interface (a previous study showed that hard materials can also have high sound absorption performance (Kuttruff, 1994); please see Sec. IV A 1 b for a discussion of the sound absorption characteristics of pitched roofs and flat suspended ceilings for CITAC bridges), resulting in a reduced reverberation time in the sound field of the CITAC bridges.

Finally, on the basis of a series of studies of long spaces, researchers have reported that "the cross-sectional shape greatly influences reverberation time in long spaces, and sound-absorbing objects (suspended ceiling), as well as sound-scattering objects (the series of columns), influence reverberation time and speech intelligibility" (Nowicka, 2020). Moreover, two studies on the effect of the cross-sectional area on the reverberation time in long spaces revealed that "with the same cross-sectional form, the reverberation time increases with the increase in cross-sectional area" (Kang, 1996c; Kim and Soeta, 2013). These conclusions are consistent with the simulation results of the sound field characteristics of the studied CITAC bridges. This further reinforces the idea that the sound fields of CITAC bridges are similar to those of typical long spaces.

Notably, previous studies on the influence of the aspect ratio on the reverberation time in long spaces have shown that "in rectangular long spaces, with the same cross-sectional area, the reverberation time is the longest when the section is square" (Kang, 1996c). However, the sound field simulation results of the CITAC bridge indicated that, for a constant cross-sectional area, the higher the height of the bridge is, the longer the reverberation time. This phenomenon may be due to the complex wooden roof structure of the CITAC bridge, which provides more diffuse reflection than the enclosure walls on the sides do. As a result, this aspect does not conform to the sound field characteristics of typical long spaces.

B. Optimal designs for the sound fields of CITAC bridges

On the basis of previous research on traditional Chinese performance spaces and the simulation results of the factors influencing the sound fields of CITAC bridges in Table VII, controlling the reverberation time inside CITAC bridges between 0.60 and 0.80 s is recommended to better meet the performance requirements. Currently, the reverberation time of the standard acoustic model is slightly less than this reference value.

The following optimizations are recommended for both newly constructed CITAC bridges and those undergoing renovation. In terms of the spatial dimensions, the length of a CITAC bridge significantly affects the reverberation time, and as the length increases, speech intelligibility tends to worsen. Therefore, the length of a CITAC bridge used for ritual activities should not exceed 50 m. Additionally, the cross-sectional area of a CITAC bridge can be moderately increased to appropriately increase the reverberation time. In terms of the enclosure structure system, the opening angle of the protective wooden panels should be maintained at approximately 15°, as this angle helps maintain the optimal reverberation time while ensuring appropriate ventilation and lighting inside CITAC bridges. In terms of the entrance style, a side entry style (with gable walls) is recommended. This style can increase the reverberation time and sound intensity. While traditional CITAC bridges typically lack suspended ceilings, for new bridges, a full or partial ceiling may be added to increase the reverberation time and overall sound quality. In terms of occupancy, reasonably controlling the number of participants in ritual activities is recommended. An excessively large number of participants can lead to a reduction in reverberation time, decreased speech intelligibility, and worsened spaciousness in the sound field, all of which negatively impact the sound field quality inside the bridge.

C. Research limitations

Owing to the time and expertise limitations of researchers, several shortcomings of this study exist. The following aspects should be explored in future research. First, the number of sound field measurements acquired on the CITAC bridges was relatively small. Increasing the number and variety of measured CITAC bridges in the future will provide more comprehensive data on the sound field characteristics of different types of CITAC bridges. Second, the field measurements of the reverberation time were conducted under unoccupied conditions, which may have led to discrepancies with the sound field characteristics during ritual activities. Future measurements could be conducted under occupied conditions. Third, one limitation lies in the treatment of the sound source input during the simulation process. Given the complexity of religious ceremonies on CITAC bridges, which often involve multiple simultaneous sound sources, it was challenging to isolate and accurately determine the sound power levels of individual sources. Therefore, the sound pressure levels in each frequency band recorded during similar activities were used as substitutes for the input sound power levels. In future research, more precise source characterization methods should be applied to improve the accuracy of acoustic simulations. Addressing these limitations in future studies would provide valuable references for the analysis of sound fields in traditional architectural structures, enhancing both the scientific rigor and practical value of such research.

V. CONCLUSIONS

Field measurements of the sound fields of four traditional CITAC bridges were conducted in this study. Then, on the basis of the measured results and survey data from numerous CITAC bridges, including their spatial dimensions and shape, a standard acoustic model for CITAC bridges was established. The sound field characteristics within the bridges were subsequently analyzed, various influencing factors were identified, and comparisons were made with traditional performance spaces from both Eastern and Western cultures, as well as with sound fields in long spaces. The key findings can be summarized as follows.

(1) The measured results indicate that the RT_{30} value of the CITAC bridges decreases from middle frequencies to high frequencies, with RT_{30M} ranging from 0.37 to 0.50 s. The mid-frequency reverberation times at both the center and the entrance of the bridges are shorter than those at the receiver located between them.

(2) In terms of the spatial dimensions, the length has the greatest impact on the sound field of the CITAC bridge. When the bridge length increases by 60%, RT_{30M} increases by 52.77%, whereas the STI value significantly decreases by 0.09. The larger the cross-sectional area or aspect ratio of the bridge is, the longer the reverberation time inside the CITAC bridge is. In terms of the enclosure structure systems, it is particularly important that the opening angle of the protective wooden panels is 15° (current condition), as this results in the longest EDT_M value in the acoustic model of the bridge. As the opening angle increases in 15° intervals, the EDT_M value decreases by approximately 10%. The RT_{30M} values of bridges with gable walls at both ends are significantly longer than those of bridges with other entrance styles. Furthermore, after a suspended ceiling is added inside the CITAC bridge, the reverberation time, STI, and $(1 - IACC_{E3})$ all significantly increase. In terms of occupancy, as the number of participants in ritual activities inside the CITAC bridge increases, the reverberation time and STI value both decrease significantly, which may be due to the unique spatial form of the CITAC bridge.

(3) As a traditional religious performance space, the reverberation time of the CITAC bridge is similar to that of Japanese Kabuki theaters with similar volumes and is noticeably shorter than those of traditional Chinese theaters, Western indoor theaters, and churches. Moreover, the spaciousness of the sound in the CITAC bridge is good, and the music clarity is greater than that in other traditional performance spaces.

(4) The variation patterns of the acoustic parameters inside the CITAC bridge are generally consistent with the acoustic characteristics of typical long spaces. Compared with typical long spaces, only the roofing form and building materials of the CITAC bridge result in differences in the influence of the aspect ratio on the reverberation time.

In this study, the sound field characteristics of CITAC bridges and the corresponding influencing factors were analyzed. These characteristics were compared with those of other Eastern and Western performance and religious spaces, and the variation patterns of the acoustic parameters in typical long spaces were examined. On the basis of this analysis, optimal designs for the sound fields of CITAC bridges were proposed. These findings improve our understanding of the sound field characteristics of CITAC bridges, with more comprehensive research on traditional CITAC bridges. Importantly, this study provides a valuable acoustic reference for the preservation of CITAC bridges, contributes to the improvement of the acoustic environment inside these bridges, and can be used to enhance the physical and mental experiences of the participants during ritual activities.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no competing interests to declare that are relevant to the content of this article.

Ethics Approval

This study does not contain any research involving human or animal subjects performed by any of the authors.

DATA AVAILABILITY

The raw data supporting the findings of this article are available from the corresponding authors upon reasonable request.

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