Large-Venue Acoustics: Arenas, Stadiums, and Amphitheaters

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Introduction

There are many unique aspects to the acoustics of large venues in cities and towns in the United States and around the world where sporting events, large social gatherings, concerts, special events, and other activities occur. These spaces have large audiences, large buildings, sophisticated audio systems, and often loud sounds associated with their use. Such spaces include arenas, large event spaces, stadiums, amphitheaters, and other large spaces that may accommodate several thousand to over 100,000 people. Seating, egress, and access for these numbers of people require large floor areas even when multiple levels of seating are used. Many of these facilities are fully or partially enclosed. The room volume becomes quite large due to the height required to get as many people as possible as close to the stage or sporting field as possible and yet not obstruct the flight path of balls in a sports stadium. Indeed, the acoustics of large venues are very different, and often more complex, than for smaller single-use venues because of the large volumes, variability in size and configuration, and their multiple types of usage. This article focuses on the unique acoustics of these very large spaces.

Acoustical Issues in Large Venues

Speech Clarity and Bass Sounds

A major issue for large venues is that there is often a need for clarity of speech for announcements, emergency evacuation instructions, and play-by-play descriptions of sporting events. Careful design of loudspeaker systems and strategically located sound-absorbent materials are used to address this issue. In fact, to ensure clarity of speech, design schemes for the facilities are studied in three-dimensional computer models where the shape, materials, and sound system are iteratively developed to fine tune their combined performance to optimize the intelligibility of sounds over the audience seating areas. Simultaneously, there is a need for loud, high-energy sound with a strong low-frequency or bass component for amplified performances in these venues. These sounds present acoustical challenges for sound within the facility such as providing enough lower frequency absorption to reduce the resonant buildup of sounds. Indeed, by including a large venue within a complex of buildings with other uses such as residential, dining, other entertainment, and hospitality near the entertainment venue provides even greater acoustical challenges to control sounds emitted out of the facility.

Home Field Advantage

In spaces where both sporting events and large concerts are held, many guests enjoy the reflected and reverberant buildup of crowd sounds often called the “home field advantage.” This means that a balance must be created between the clarity of speech and music sounds and the passive reinforcement of cheering by guests to keep the space lively. Thus, the ceiling and wall elements are shaped to provide reflective reinforcement of sounds made by the crowds that reaches out to others in the crowd as well as players on the field.

Building Services

When the spaces are partially or fully enclosed, large air-conditioning systems are required. Thus, a noise- and vibration-control design is needed to reduce the sounds from the air-conditioning equipment that are propagated into the facility and limit off-site noise propagation from the building to adjacent properties.

Audio and Video Systems

The design and control of audio, video, broadcast, and technical communication systems in these buildings is a complicated exercise involving multiple design team members because achieving uniform sound coverage

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from loudspeaker systems with adequate clarity and full-frequency response is often challenging due to the large seating areas and geometry of the venues. Furthermore, the design of viewing systems, including large scoreboards with video displays, must account for viewing angles for all members of the audience who are spread over very large areas. Control of ambient light in outdoor venues can help improve the visibility of the screens. In addition to the house systems, rental and touring systems are often used in these venues, further complicating the audiovisual (AV) system design and operation.

Sound Emissions
Large venues are often constructed in or near built-up areas so that a large population base has access to the facility. However, this means that sound-sensitive neighbors may be located close to the facility. To deal with this, iterative studies of sound propagation from the facility are often done during design to understand how the sounds from the facility may impact the surrounding community. This often involves three-dimensional computer models of the facility with the sound system loudspeakers and the shape, materials, and design features of the buildings and the surrounding buildings are constructed as part of the process.

Municipalities may also have special entertainment sound regulations. The use of sound-monitoring systems during live events is often included in the design and operation of the venue, enabling the facility operators to know how loud the sounds are at locations in the community to help avoid situations where the sounds exceed local regulatory limits.

Health Concerns
Although many people enjoy the experience of listening to events with high sound levels and the thrill of crowd responses at sporting events and concerts, these levels also bring concerns for sound-related health effects. These include temporary and permanent threshold shifts and possibly hearing loss as well as physiological effects including high blood pressure and circulatory and respiratory effects among others. Many concert venues include warnings and disclaimers at the venue and as part of the ticket purchase in acknowledgment of the potential health hazards. Indeed, the 2018 Environmental Noise Guidelines by the World Health Organization (WHO; see bit.ly/3sODnWW) has recommendations for limiting recreational sound exposure and is encouraging additional research on the health effects of high-level entertainment sounds on audience members and working staff due to the transient nature of the exposure.

Outdoor Music Venues
Precedents
Ancient Greek and Roman amphitheaters with a raised stage a stepped, semicircular seating area set into the topography, and a natural acoustic sonic projection to a large audience is a prototypical typology for the outdoor music venues of today. More recently, bandstands were built in many communities for nonamplified sound sources such as a local band or performance group. Sometimes, a small sound system consisting of a microphone and one or two loudspeakers on stands would be used so an announcer or single performer could be heard at greater distances from the bandstand.

Acoustical Design Issues
The historic precedent of the bandstand on the village green has been transformed into facilities with larger audiences, higher power sound and video systems, and more frequent uses in many communities. Thus, the architectural acoustic design of these venues was significantly changed by the transition from natural acoustic sound propagation to completely amplified sound to accommodate larger audiences and higher sound levels. As the venues grew, acoustic issues changed to provide the most effective sound experience for the audience.

Related to the size of the venue, another issue that arose as venues got larger is that many facilities host a wide variety of performance types. These range from community orchestras and meetings to large touring groups and multiday festivals with large line array loudspeaker systems and rows of subwoofers for a wide variety of lively modern music genres.

Passive and active variable acoustic systems can be employed to adjust the acoustics for different types of performances and sizes of audiences in these venues. For a small venue, active systems may include electronic architecture systems that have a network of loudspeakers located over the stage and throughout the venue to add reflections on the stage so that orchestra members can hear each other. Reflective and reverberant enhancements can also be added to sounds heard by the audience. Adjustable acoustical elements can include moveable sound-absorbent, reflective, and diffusive panels on the walls and roofs of the facility and adjustable stage floors among others. Small outdoor performance venues may have a permanent stage with an angled or curved roof to provide hang points for rental lighting, audio, and video systems and for poles along the perimeter of the seating area for delay loudspeakers to serve the outer seating areas for larger events. A back-of-house building can be used to shield adjacent homes from sounds.

A medium-sized outdoor performance venue may have a stage in a permanent structure, with structural hang points to hold large video displays and line array loudspeakers. The stage is often lined with perforated-metal sound-absorbing panels so that sounds from the monitor loudspeakers used by the performers on stage so that they can hear each other do not reflect back to the audience. The facility can also have large doors that can be opened on the front and back during warmer weather for views and to allow breezes to blow through the facility but that can be closed when not in use to protect equipment stored in the building. Poles for delay-ring loudspeakers used during larger events are located around a paved ring around the perimeter of the seating area. There is often no fixed seating, but instead, the audience brings lawn chairs and blankets to enjoy the performances in a relaxed atmosphere.

A large amphitheater with 4,000 folding seats under the canopy and room for an additional 5,000 to 10,000 people or more on the lawn and other surrounding areas in a medium-sized city is shown in **Figure 1**. The canopy has a sound-absorbing inner liner to reduce reverberant sound buildup under the roof. The curves of the roof were carefully designed to minimize sound focusing for the audience and performers, whereas the vertical walls in the stage area are lined with thick sound-absorbent panels to reduce sound reflections to the audience. The main loudspeaker arrays, monitor loudspeakers, video displays, and control consoles are rental or touring company equipment. Delay-ring loudspeakers are part of the permanent equipment at the facility. A sound-monitoring system was included as part of the operational plan for the facility.

Figure 1. *Large amphitheater with a covered roof and open lawn seating area.*

Domed Stadium Community Noise and Room Acoustics Considerations

Indoor stadiums present acoustical challenges that are different from more typical spaces when considered at the scale of a 65,000 to 100,000+ seat capacity. The primary concern is how the building materials affect the inside-to-outside sound transmission. Most stadiums feature relatively lightweight construction outboard of a concrete structural frame and seating risers. The exterior skin can feature a significant amount of glazing and/or lighter weight curtain wall construction that provides minimal sound transmission loss at the low frequencies that are part of modern popular music.

From a noise control perspective, typical community concerns apply, such as outdoor mechanical-plant noise levels and, more importantly, sounds from amplified music concerts held inside the stadium propagating to neighboring properties. The concert sound levels are not necessarily higher than at other concert venues. However, the total sound power can be higher due to the combination of sounds from the main loudspeakers at the stage and supplemental "delay/fill" loudspeakers employed by some productions to cover remote seating areas and hard to reach locations in the corners of the facility. In addition, loudspeakers that are located away from the stage must have digital delays added to the signals to slow down or delay the sounds played through them so that the delayed sounds arrive correctly aligned in time, slightly after the sounds traveling directly from the stage. This is because the sounds traveling through wires, unless delayed, will reach audience members before the sounds from the stage that are traveling through the air. The house sound system may also be used to cover some seating areas.

More importantly, the roof construction can feature even lower mass than the exterior walls, with metal roof decks with rigid foam insulation and single-ply rubber roofing

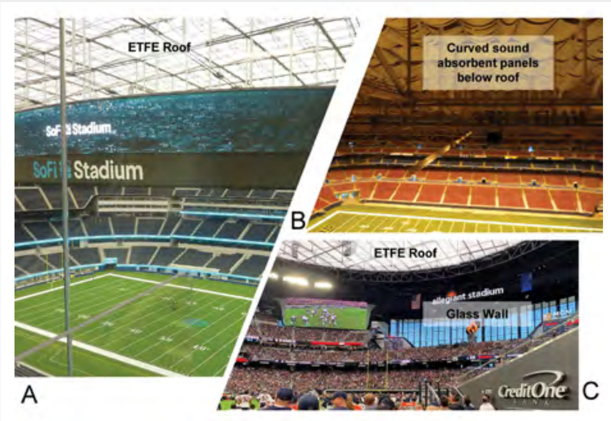

Figure 2. *Stadium roof systems.* ***A:*** *SoFi Stadium in Inglewood, California, setup for American football with an ethylene tetrafluoroethylene (ETFE) roof system.* ***B:*** *dome at America's Center in St. Louis, Missouri, that has a conventional roof with suspended baffles for acoustical treatment.* ***C:*** *Allegiant Stadium near Las Vegas, Nevada, that has a moving glass end wall and ETFE roof.*

materials or even lower mass, translucent ethylene tetrafluoroethylene (ETFE) plastic roofing systems (**Figure 2**). ETFE panels can be a single layer supported at the ends or a double panel with a pressurized airspace between the two panels. One advantage of the relatively lightweight construction is that the effective low-frequency absorption is substantial for the roof, and especially for the ETFE sections, because the low frequencies simply pass through.

Furthermore, typical, air-pressurized ETFE roofs are highly reflective at speech frequencies, and the pressurized cells have a drumhead resonance that is audible when hundreds of the same-sized cells are vibrating at the same frequencies. Suggestions to stagger the size of the ETFE cells to reduce the resonance have been rejected by structural engineers not wanting to add complexity and cost to the support systems.

The ETFE roofing systems weigh around 1.46472 kg/m^2 (0.3 lb/ft^2) excluding the support framing and primary building structure, with transmission loss values of 6 dB or less in the 200-Hz and lower octave bands. In addition to the roof having the lowest overall transmission loss of the building exterior elements, it is also the single largest surface, so the radiation of sound through the roof can be the most significant component of the noise traveling to adjacent properties, especially if they are elevated and have a line of sight to the stadium roof. Where local noise ordinances have C-weighted or octave-band sound level limits, it can be hard for a concert event to comply with sensitive nearby neighbors without either interior noise level limits on the performers or additional mitigation in the building structure. Full or partial ETFE roofs are featured in recently built stadiums in Minneapolis, Minnesota; Los Angeles, California (**Figure 2A**); and Atlanta, Georgia, the latter also having some ETFE exterior wall area, and for a proposed facility in Nashville, Tennessee.

Room Acoustics

Clearly, the room acoustics of domed stadiums are notoriously difficult and, at first experience, confusing. When a small group of people meet at the periphery of the field speaking in relatively low-level sounds, the space behaves as if it were an outdoor stadium. This is because the sound source (the people) does not fully excite the space and because the reflective surfaces are so far away that distance loss reduces the sound levels to a point where they aren't heard as echoes. However, with very loud sounds, such as a high-energy, amplified concert or a large crowd cheering during a sporting event, the domed stadium can have a very reverberant character, with significant echoes.

This dichotomy in the acoustics of the stadium between when it is empty with just a few people speaking and when it is fully occupied with an active crowd is due to the combination of the very large interior space of the stadium and the materials used to construct and finish the bowl-shaped seating area, which is among the largest single volume interior spaces in the world. The scale of these spaces is large enough that the traditional methods of calculating and measuring reverberation tend to fall apart because the acoustical energy required to create a homogenous sound field in the spaces is larger than one might expect and the distances that sound travels from a source to many reflecting surfaces are impacted by distance loss/air absorption. For this reason, conventional reverberation time (RT or $T60$) calculations tend to overestimate the reverberation time and a correction for spaces with a mean free path of over 61 m (200 ft) has been suggested (Wrightson and Johnson, 1994).

Early measurements in the Houston Astrodome, Houston, Texas, with a small interior volume compared to more recent domed stadiums, often used yachting cannons and other firearms firing blank cartridges as sound sources for making acoustical measurements. Even these loud sources often resulted in simply measuring the decay of the reflections rather than the complete reverberant sound decay because the space was not fully excited by the source sound. This can be appreciated if one considers the interior volume can be as large as 226,534 m^3 (8 million ft^3). This volume of air has a mass of about 283,495 kg (625,000 lb), or about the same mass as that of 1.5 diesel train locomotives. Moving that much mass requires a significant amount of acoustical energy.

Acoustical Treatment

Acoustical treatment for domed stadiums faces the same challenges of appearance, abuse resistance, space requirements, and cost as it would for any other building. However, there are two very significant differences with domed stadiums, the most important being the area to be treated. The stadium roof can be nearly 2.3 hectares (7 acres), and so the cost of treating the entire roof can be substantial. This is further complicated by the current architectural design trend of trying to introduce as much natural light as possible into the seating bowl, leading back to translucent ETFE being used for the roof because it is more architecturally flexible, lighter, and less expensive than traditional glass systems. The glass systems are still used for vertical surfaces, especially operable walls, at the end of domed stadiums that can open and close as seen at Allegiant (**Figure 2B**; see bit.ly/AT-GS1), Lucas Oil (see bit.ly/AT-GS2), and AT&T (see bit.ly/AT-GS3) stadiums.

The net result is that when the project budget allows, nontranslucent surfaces are treated with conventional sound-absorbent materials, such as wall panels and suspended baffles. Stadiums in St. Louis, Missouri, and Toronto, Ontario, Canada, have extensive roof sound-absorbent treatments, made possible by their solid, metal deck roof systems. St. Louis uses a suspended baffle approach (**Figure 2C**), whereas Toronto features applied fiberglass board to avoid wind issues with its operable roof.

How are these acoustical challenges addressed? For sporting events, with a premium for natural light and an emphasis on speech intelligibility from the house sound system, fixed sound-absorbent treatments and careful sound system design, setup, and operation are required. The key for a successful sound system design is controlling the directivity of the loudspeakers and speaker arrays to minimize sound hitting nonseating areas and to limit the overlap from other loudspeaker zones that can create delayed arrivals impacting intelligibility. The threshold design and system setup goal is to achieve Speech Transmission Index of Public Address systems (STIPA). STIPA values can fall between 0 (no intelligibility) and 1 (perfectly intelligible). Thousands of STIPA measurements in dozens of sports facilities have indicated that there are minimal speech intelligibility complaints from spectators when a 0.55 STIPA value is achieved.

In contrast, for concerts, natural light is not expected and can interfere with viewing the LED video displays and theatrical lighting, along with the fact that most such events occur in the evening. Use of the building for both sporting events and concerts provides the opportunity to provide temporary acoustical treatments, most commonly synthetic velour drapery for vertical surfaces such as glass end walls and, in rare cases such as the Houston Livestock Show and Rodeo concert series, over the translucent portions of the roof. There has been some investigation of permanent and variable acoustical systems for domed stadium roofs. However, none of these concepts have yet survived the budget pressures of the projects.

Good sound quality and speech intelligibility can be difficult to achieve in domed stadiums. Even when optimized, differences in speech clarity and musical quality may be experienced across the seating sections. This is especially true for concerts, where the best sound quality occurs at seats where the direct sound from the loudspeakers has very high direct levels compared with multiple arrivals from reflections and other loudspeakers. Seating where the reflected and reverberant sound levels are closer to or exceed the level of the direct sound are at a disadvantage.

Large Arena Venues

Arenas typically have seat counts of between 5,000 and 25,000 people that is often similar in seating capacity to amphitheaters. However, these venues often have smaller seating capacities than stadiums. The main arena bowl is usually a fully enclosed, large-volume space presenting unique acoustic challenges. The stadiums and outdoor performance venues previously discussed are partially or wholly in the open air that allows some dissipation of the high sound levels so there is not as much concern about room acoustic design and finishes as in arenas. Although there are similarities in the different types of large venues in terms of bringing large numbers of people together to listen to and participate in group events, the acoustical challenges in arenas are perhaps more critical and focused than in traditional acoustical concerns, more so than in the other large venues.

The multiuse arena form emerged in the United States during the 1960s and was originally used for both basketball and ice hockey. A visual focus was created on the player or performance surface, usually the lowest point in the arena, with seats arranged 360° around it. Stepped seating allowed sight lines for audience members, providing a full view of that surface. The view of the players/performers or scoreboards/other visual media often took priority, and little attention was given to acoustics.

By the end of the 1960s, however, arenas were often the location of choice for live pop music acts to play as concerts became more prevalent. Acoustics in these venues were a challenge from the outset due to the large volume of the spaces and insufficient sound-absorbing treatments. Large, stacked loudspeaker systems were often located on an end stage to push out high sound levels that often struggled to provide coverage over large parts of the audience. The speaker stacks also resulted in "echoes" of speech and music when sounds propagated out from the speakers and reflected back to the stage or front seats as "slap back" echoes, with long delays in arrival compared with the direct sound.

Over time, the arena form developed to accommodate more event types, with these shaping the surface or stage into a way that could improve the acoustics. The most common developments were the rectilinear box with seats around the perimeter; horseshoe bowl; full bowl with seats in an oval shape surrounding the playing field; and large fan where the side walls angle out from the stage. In suburban locations, where noise emission was not an issue, lightweight, parabolic, concave roofs were inexpensive and efficient to build. The negative issues of the larger interior volumes and poor sound isolation were not considered a major concern given the limited options for where events could be hosted.

Three sound system forms dominated in these types of arenas: the central cluster, distributed clusters, and fully distributed systems. The advantage of the latter two forms was typically smaller groups of loudspeakers that did not interrupt sight lines, with the ability to receive a feed from the mix of a live event and supplement touring sound systems to provide coverage in the hard-to-reach areas farthest from the stage. This saw the central cluster almost entirely phased out by the early 1980s.

Acoustic design was considered a priority during the mid-1990s, when a confluence of issues resulted in a shift of emphasis.

- Demand for live music began to increase, and large venues returned to urban centers, often as regeneration projects. Multiple large venues began to compete for events.
- A statutory requirement demanded that places of public assembly have public address/voice alarm (PAVA) systems capable of intelligible speech in emergency situations.
- Advances in sound system technology resulted in house and touring systems capable of much higher sound levels, at significantly improved quality, particularly at low (bass) frequencies, This has resulted in the need for the careful design of interior room acoustics, including both provision of appropriate acoustic finishes and minimizing the reverberant interior volume of the space.

High concert sound levels and location of venues in urban areas require higher sound-insulating building envelopes to achieve stringent noise limits at surrounding residences. This requires a clear understanding of nearby noise-sensitive receptors such as dwellings and hospitals at the outset of a project so that an adequate sound-insulating performance can be achieved. This typically has a significant impact on the architectural and structural design of the building, especially the roof. Getting it wrong is usually extremely costly or impossible to rectify once the arena is opened unless a conscious decision is made to be able to easily add components to the primary constructions later.

Today, the acoustic experience of the arena interior and its impact on the environs is considered the paramount design concern for a successful facility. Consequently, fundamental design decisions, including the site and orientation, bowl form, height, roof shape, roof geometry, and interior finishes, require acoustical input from the earliest stages of a project.

Acoustic Features

The resulting size and shape of the arena cannot always provide a natural room acoustic response consisting of a strong direct sound, early sound reflections from overhead and the sides, and diffuse reverberation for the audience and supportive reflections for the performers to be able to hear each other while playing because the room surfaces are long distances away from the listeners. Instead, sound quality is facilitated by audio systems that must provide a uniform loudness and frequency response of direct and reflected sounds over the entire audience area; maintain directional cues to the location of the sound sources; and have arrival times of sounds from direct and fill loudspeakers that reinforce the sense of sounds coming from the stage while surrounding or immersing the audience in a spatial audio-listening experience.

All of this means that the room acoustic design must support and complement the sounds propagated from the loudspeakers. For example, controlling sound reflections from natural acoustic and amplified sources to avoid long delay times and confusing directional cues is critical to a successful acoustic outcome. Moreover, room volume must be minimized as much as practical to reduce excessive reverberance, and the height and length of the arena should only be what is required to get the audience as close as possible to the performers and for audio, visual, lighting, and theatrical equipment to function.

Arena room volumes are inherently large, with the height driven by the need to achieve optimal sight lines along with a safe riser height for the successive rows of seating. The geometry of the roof is a major factor in this regard. Close collaboration among architect, structural engineer, and acoustic consultant is required to optimally resolve these often competing design challenges. Preference should be given to flat or convex roof forms as viewed from the interior. Concave or parabolic forms that increase the room height and volume and focus the sound should be avoided. Floor area that extends significantly beyond the last row of seating should also be avoided.

It is usually necessary to introduce significant areas of broadband and low-frequency sound-absorbing and sometimes diffusing treatments on walls, soffits, and the underside of the structural external envelope to reduce strong reflections from the sound system striking these surfaces because the reflections can negatively impact speech intelligibility and music clarity. Vertical and horizontal glass surfaces usually need to be angled to reflect sound energy directly to a sound-absorbing surface to avoid creating echoes. Sound-absorbing finishes should be effective across the audible frequency range, with increasing attention required for low-frequency sound control. This usually requires the acoustical design of a special ceiling system that includes relatively thick sound-absorbent material suspended about 2 m below the roof, with sufficient gaps to get a maximum sound-absorbing performance from both the front and rear sides of the material as well as additional low-frequency panel absorption from the suspension of the material. The need for these materials in fully enclosed arenas is perhaps greater than in open air or partially enclosed amphitheaters and stadiums because the absorption of the low-frequency sounds by the panels is the only way they can be reduced. There are no large openings for the long-wavelength, low-frequency sounds to escape from the venue. Finally, the floors usually need to incorporate some impact sound control but generally do not include any carpet due to maintenance issues.

Sound-absorbing seats are used throughout the bowl to minimize acoustic differences between the unoccupied and occupied conditions especially during setup, testing, and sound check prior to events when an audience is not present in the room. Some spaces may require variable acoustics to accommodate different performance types. This can be especially true in rooms where the roof is be opened. The incorporation of audio and visual technology systems, control rooms, and similar spaces that connect to the main performance space all need to be considered. When used as elements in an integrated holistic approach to the architectural and acoustical design of the arena, these concepts should result in a sufficiently controlled room that supports the sound system and reaches criterion levels for acoustical quality.

Case Study: Barclays Center

The Barclays Center arena in Brooklyn, New York, required acoustical renovations when its original lightweight roof resulted in a lower than ideal inside-to-outside sound reduction, resulting in noise impacts to surrounding residences. The structural capacity of the roof would not accommodate significant weight being added to the existing building. Thus, rather than add weight, off-site sound emissions were reduced by installing a green roof

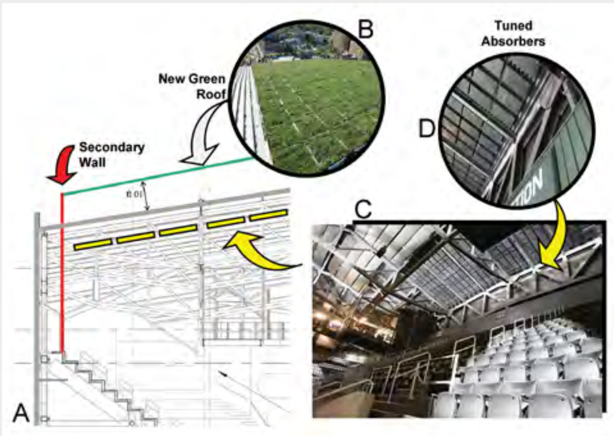

Figure 3. ***A:*** *concept section drawing of the Barclays Center in Brooklyn, New York.* ***Green line:*** *new green roof above the original roof.* ***B:*** *photograph of the new green roof installed as a second roof layer above the existing roof to reduce off-site sound transmission.* ***C:*** *interior photograph showing tuned resonant-absorbing panels above the seating area.* ***D:*** *enlarged photograph of the absorbing panel, with a metal facing and absorbent fill suspended below the main roof of the building.*

system of modular, prefabricated sedum trays that form the base for the green roof to allow vegetation to grow, hold water and nutrients, and root above a structural roof deck (see **Figure 3**; also see bit.ly/AT-GS5).The trays are inherently damp due to the properties of the sedum, located 10 ft above the original roof. The green roof, combined with the airspace between it and the original roof, provided improved sound isolation while meeting the original masterplan concept for a green roof.

Inside the room, the parabolic roof form, initially chosen for structural efficiency and weight, resulted in a larger than ideal acoustic volume. This led to complaints about the clarity and quality of sound throughout the arena, especially on the event floor, upper seating bowl, and seats furthest from the stage when the room was used for musical events.

To solve these problems, the interior acoustics were upgraded by the addition of metal sound-absorbing panels over an enclosed airspace, tuned to absorb 50- to 100-Hz energy placed across the entire upper audience seating area, helping to reduce the overall sound pressure level. The house sound system was also optimized to accommodate individual time delays to the upper bowl loudspeakers, allowing them to be individually time aligned with sound from the stage system, providing a significantly improved audience experience. The design concepts for the renovation of the space are illustrated in **Figure 3**.

The Outlook for The Future

Technology continues to be used in creative ways as part of sports, concerts, and other large-scale entertainment events as a mechanism to transform a relatively passive engagement into an active, immersive experience for performers and audience. Therefore, large arenas, stadiums, and amphitheaters around the world are likely to become more technology intensive in the future. Technology infrastructure requires careful planning and must allow for easy connection or deployment of new technology in the architecture. The design challenge is how to give the space architectural character while allowing this technological overlay to happen seamlessly. The use of technology, including emerging immersive audio and visual (VR), augmented reality (AR), and extended reality (XR), as well as development of new concert and performance formats and emerging sports (e.g., eSports) will have a continuing impact on the future development of the typology and the acoustical design issues involved.

Large-scale performance spaces, whether inside or outside, pose inherent design challenges given the number of spectators they entertain and the difficulty in containing sounds of heavily amplified performances. Many people go to these spaces to share a collective experience with a group of people, to have community, enjoy the event, and leave energized by the whole experience. However, there are also many who are unwilling participants in the performances, who experience the by-product of the event without immersion in the event. An on-going dialog between the performance venue and its nearby inhabitants via personal communication and technological systems is needed so that multiple viewpoints are considered.

As technology moves ahead, perhaps new and creative ways to further improve the acoustic environment of large-scale performance venues internationally will develop that may help to further optimize the participants' experience and reduce the impact to the surrounding community. The use of meta-materials, active phase cancellation of sounds with loudspeakers, and other interventions are on the horizon to provide the performances of the future with even better, more controlled sound fields and more optimized acoustic environments. Research challenges for effective lightweight materials that can absorb low-frequency sound and reduce emissions from facilities to surrounding areas, to spatial audio and visual systems for large venues, and to hearing health concerns for recreational noise exposure are issues requiring future development.

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