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GRAVITY-LESS IN ARCHITECTURE AS A DESIGN PROBLEM: CASE STUDIES OF SINGAPORE NATIONAL STADIUM AND MERCEDES-BENZ STADIUM, ATLANTA

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Abstract

Sports Stadiums have the capabilities to invite a large crowd, therefore the need to cover a large span to cater to a maximum number of people without affecting the viewpoint and comfortability of the public to enjoy the sports becomes the foremost factor in their structure. In this light stadium Structures are unique in themselves as they require to be column-free, high span, and open plan. Through the help of case studies and comparative analysis of different structures, it can be observed that Gravity-less Structure can be made by using Trusses and Spaceframes Structures. More ever moveable structures can also cover long spans. To conceptualize this problem case study of Singapore National Stadium is chosen for this assignment. The project uses spaces trusses interlinked with louvers that allow the structure to cover a span of 312 m with a height of 80 m and making it the world's largest dome. The upper part of the Roof is Moveable depending upon the use of the Stadium. The structure moves along the outside vault, from the closed to the empty location, the reinforcing framework of the moving areas is planned with adaptable associations, allowing the structure to stop and twist under the activity of gravity. The roof system uses a space truss structure. The structures are arranged like a half-ball dome. Thus, a wide enough distance can still be covered with lightweight and strong materials.

INTRODUCTION

Gravity-less architecture refers to a design strategy in which design and image of buildings are developed to confront the pre-conceived notions of gravity (Shah et al., 2023). This paradigm does not literally overturn the concept of gravity (Shah et al., 2023b), but rather plays with the formal and material qualities of structural systems, suspension and defying the logic of traditional load-bearing, to create the illusion of weightlessness, suspension or apparent defiance of gravity (Allen & Iano, 2019; Ching, 2020). Architectural strategies include cantilevers, floating volumes, tensile structures, diagrid frameworks and exoskeletal systems to spread loads around in unconventional ways, so that building elements can seem suspended (Bhatti et al., 2025), leaning or seemingly floating off the ground plane (Engel, 2007). In the current architectural debate, gravity-less design has become an important manifestation of technological advances, architectural experimentation and conceptual aspiration, and a response to the changing nature of the interactions between architecture, engineering, and human perception (Frampton, 2007; Jencks, 2011).

GENERAL REASONS FOR GRAVITY-LESS ARCHITECTURE

Gravity-less architecture is used to question the concept of weight, stability and structural order, and to harness cutting-edge engineering and material technologies (Bhatti et al., 2025). It lets architects play with lightness, expression and space efficiency, thus meeting the contemporary demands of the urban, cultural and experiential (Bhatti et al. 2025). This is not an effort to defy gravity, but rather an intelligent use of and control over the forces it brings down, to create innovative, progressive and technically-evolved architecture.

Reason	Explanation	In-Text Reference
Structural and Material Innovation	Advances in high-strength steel, post-tensioned concrete, and composite materials enable long spans and reduced structural depth, creating the illusion of weightlessness through efficient load redistribution.	(Allen & Iano, 2019; Ching, 2020)
Iconic and Expressive Form	Gravity-defying designs enhance visual identity and landmark value, symbolizing innovation and futurism in competitive global urban contexts.	(Jencks, 2011; Koolhaas, 1995)
Spatial and Functional Flexibility	Minimizing ground contact and concentrating supports allows open public spaces, column-free interiors, and adaptable layouts suited to dense or constrained sites.	(Ching, 2020; Leach, 2009)
Urban and Environmental Response	Elevated or suspended forms address site limitations, pedestrian continuity, landscape integration, and environmental challenges such as flooding or topography.	(Leach, 2009)
Experiential and Conceptual Intent	Concealed structural systems create visual tension and sensory engagement, reflecting a shift toward experiential perception over explicit structural legibility.	(Pallasmaa, 2012; Frampton, 2007)

Table 1General reasons for using Gravity-Less Architecture; Drawn by author

SINGAPORE NATIONAL STADIUM

The National Stadium at Singapore Sports Hub is a multi-purpose sports stadium with a seating capacity of 55,000 seats that caters for a variety of sporting and recreational activities throughout the year (DP Architects, 2014). The stadium is designed to be flexible and adaptable, with the ability to host a variety of activities and events. The stadium can be configured for different events, such as sports, concerts, and other public gatherings, and it is designed to be easily moveable so that the roof and seating can be quickly removed and replaced. The free span dome structure is one of the most unique architectural and structural elements of the project and is one of the world's largest of its kind, featuring a retractable roof to protect the playing field from the heat and rain that can occur in a tropical climate (DP Architects, 2014). The roof structure also includes a wide LED lighting system—a network of lights that makes up one of the largest integrated LED displays in the world—and plays a key role in making the stadium a prominent landmark in the city (ArchDaily, 2014). The stadium is designed specifically to address the climatic challenges in Singapore by adopting an innovative air-cooling approach considering occupied areas, which enhances the thermal comfort of the space, while also minimizing the total energy use of the project (DP Architects, 2014).

ANALYSIS OF STRUCTURAL PROBLEM AND HOW IT WAS SOLVED

The open roof structure creates a continuous shade and weather protection for the seating bowl with 55,000 seats, the concourse ticketing areas and an adjacent, publicly open internal street. The large free span design allows the stadium to have no internal columns, which further strengthens the spacious sense of the stadium, and provides the stadium with a complete visual visibility throughout the stadium (Liu & Lim, 2010).

Structural Design Requirements

The structural system was developed in response to the following key design criteria:

- **Column-free, open-plan configuration** to ensure unobstructed views and spatial flexibility
- **Protection from rainfall** to enable year-round usability in a tropical climate
- **Solar shading and humidity control** to enhance thermal comfort for spectators
- **Accommodation of multiple sports** within a single adaptable facility

These requirements collectively informed the gravity-less structural strategy adopted for the stadium roof, integrating long-span engineering with environmental and programmatic performance.

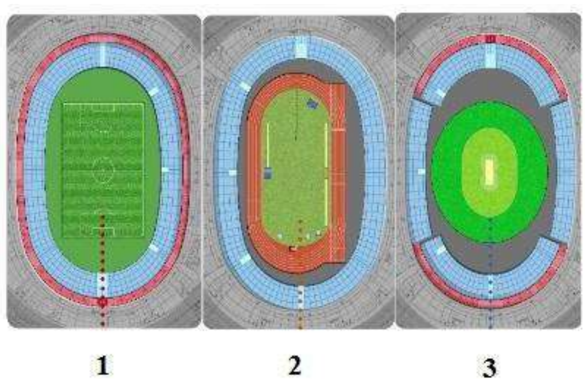


Figure 1Football, Cricket and Athletics Mode

SHELL STRUCTURE

There are 6 main arches across the width of the long axis of the seating bowl and the roof is the principal structural system. The arch structure holds up the tracks where the retractable roof panels move and is the only visible structure from the central void when the roof is open (Liu & Lim, 2010). A series of secondary interlocking arches finish the roof structure, which is fixed, making it continuous and integrated. The spatial configuration of these structural elements creates a complex three-dimensional geometry which distributes loads in various directions, thus improving structural efficiency and optimising member depths. The roof adopts the configuration of interlocking arch, which has the property of inherent structural stability and redundancy (Liu & Lim, 2010). All the roof arches are tied together with a single tension ring beam that is very important to the stability of the structure. This ring beam is a prestressed concrete structure that will extend around the entire stadium perimeter at the stadium's concourse level. It is encased in a sequence of columns which carry the vertical loads of the roof arches to the foundations as well. The continuity of the ring beam, and the shell action of the roof means that there is no need for movement joints in the main fixed roof structure. The ring beam and supporting columns play a role of vertical portal frames and cantilever to resist destabilizing forces acting on the roof system (Liu & Lim, 2010). There are two main architectural and aesthetic factors that control the design of the shell trusses. First, it was necessary for all the intersecting arches to have equal width at the point of intersection, and second, all the bottom chords of the trusses converged at a common point. Two levels of a structural grid run parallel to the short axis of the seating bowl, the other developed radially according to the spherical geometry of the dome. The result is that the sections of the truss are arranged vertically, which means that the bottom chords are always perpendicular to the surface normal. The geometric rule applied is consistent throughout the fixed roof: The centerlines of top chords follow arcs on the upper part of the roof, while the bottom chords follow the geometry of the lower part of the roof (Liu & Lim, 2010).

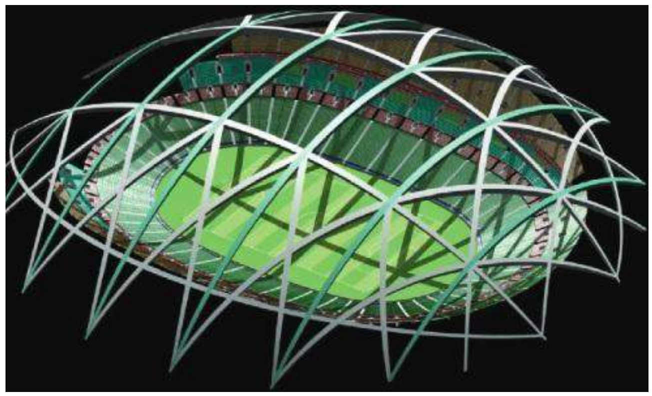


Figure 2 Left- The Trusses and interlinking perimeter beams, Right-Trusses in scale with Seating Bowl Source: Hladik, P., & Lewis, C. J. (2010). Singapore National Stadium roof. International Journal of Architectural Computing, 8(3), 309–328. http://papers.cumincad.org/data/works/att/ijac20108302.pdf

MOVING ROOF

The retractable roof system is made up of two main movable panels, each measuring around 210 m in length and 49 m in width, supported by a series of bogies which allow for controlled movement. These bogies move along four parallel runway beams which are part of the fixed roof system (Hladik & Lewis, 2010). A completely sealed connection between the fixed and movable roof parts is not included, but the connection is designed to keep the wind-driven and blown rain from getting into the stadium's interior. Moreover, a continuous waterproof seal is ensured between the two movable roof panels at the fully closed position of the roof to keep rain water out while providing environmental protection without sacrificing the flexibility of the system (Hladik & Lewis, 2010).

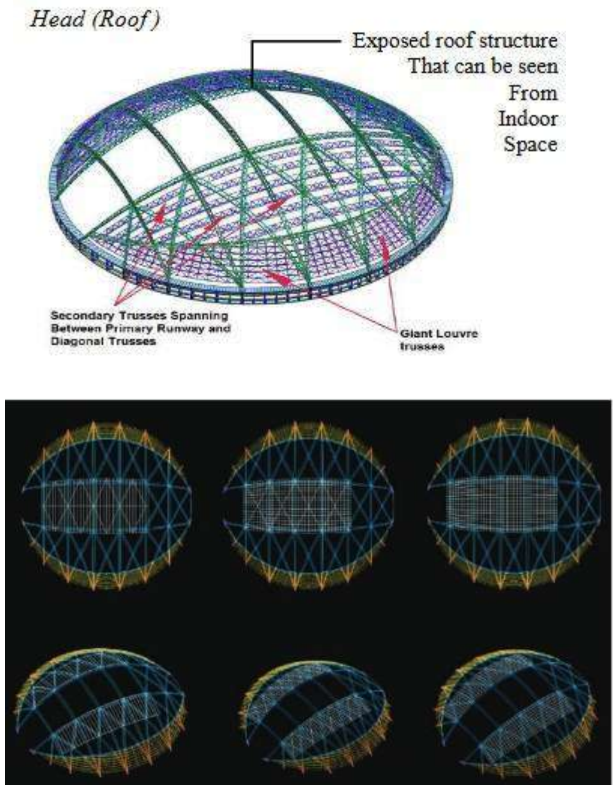


Figure 3 Left: Moving Roof and Louvers Source: Tekla. (n.d.). Singapore Sports Hub National Stadium roof: Moving roof and louvers. Tekla Campus. https://campus.tekla.com/singapore-sports-hub-national-stadium-roof Right Retractable Roof and Trusses Hladik, P., & Lewis, C. J. (2010). Singapore National Stadium roof. International Journal of Architectural Computing, 8(3), 309–328. http://papers.cumincad.org/data/works/att/ijac20108302.pdf

LOUVERED AREAS

The promenade becomes a public space that is contiguous and sheltered for the public, while providing the continuity of vision and space with the interior of the stadium. A series of radial hangers along the concourse suspend a system of overlapping louvers fabricated from stretched PTFE fabric to provide shade on the external concourse (Hladik & Lewis, 2010). This horizontal arrangement of louvers was required to meet a number of performance criteria: 30-degree minimum overlap angle to provide effective rainwater runoff; solar shading of circulation spaces below; minimal obstruction of viewing outwards from concourse levels 4, 5, 6 and 7; reduction of the amount of fabric surface area to maximise material efficiency (Hladik & Lewis, 2010).The shape of the louvers is determined by two main set out surfaces of the roof: the sphere and the torus. The bottom louver is designed to sit level with the horizontal floor at Level 4 and the overlap angles are calculated at the ends where the dome surfaces are highly curved. However, because of the intersection between the horizontal plane and the spherical set-out surface, the horizontal arc on the torus is not a circle, but a curve that has different lengths between the sphere and the circle. As a result, the overlap angle becomes greater further away from the short axis of the seating bowl, making a significant impact on the whole louver system. This geometric situation significantly affected the design of the 14 louvers each of which is about 350 m long and 5 m wide (Hladik & Lewis, 2010). The concourse zone with louvered openings also serves as a main circulation corridor, directing pedestrian flow, as well as offering access to the social plinth. This intermediate spatial layer improves the socialization, circulation and protection of the environment while creating a whole architectural and structural framework that allows public access.

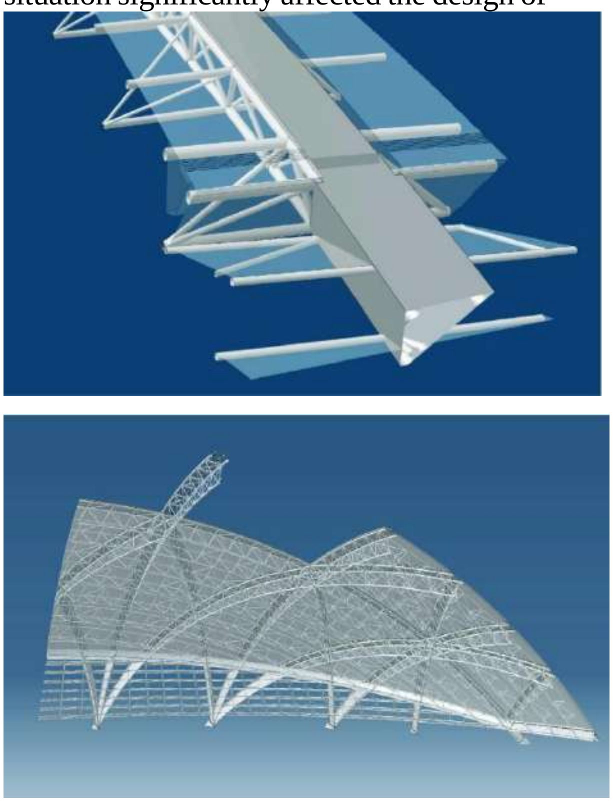


Figure 4 Louvers Source: Hladik, P., & Lewis, C. J. (2010). Singapore National Stadium roof. International Journal of Architectural Computing, 8(3), 309–328. http://papers.cumincad.org/data/works/att/ijac20108302.pdf

The louvered concourse at the Singapore National Stadium acts as a protected circulation space that guides the movement of people through the stadium and to the social plinth. The plinth serves as a transitional public space, seamlessly connecting the various areas of the stadium, including the gathering space, the leisure area, and the pedestrian area. The social plinth helps to increase the comfort level for users, helps to facilitate smooth movement, and strengthens the stadium's relationship with the rest of the public sphere, with a design that is both structurally innovative and socially and functionally engaging (Hladik & Lewis, 2010; ArchDaily, 2014).

STRUCTURE AS AN ENVIRONMENTAL SHIELD

The Singapore National Stadium's structural design plays a key role in creating an environmental shield by providing a full canopy over the stadium arena with 100% shade for all spectators, thanks to the incorporation of a lightweight ETFE-clad moving roof. The retractable roof is closed before events to reduce the exposure of the bare concrete mass of the seating bowl to the heat from the sun. Furthermore, the roof is covered with insulated, aluminum-reflecting panels, reducing radiant heat gain and creating a more comfortable environment in the stadium. The mobile and static roof components illustrate how structural design can ensure the stadium is capable of actively controlling the environment, while maintaining its architectural and functional performance (Hladik & Lewis, 2010; Dezeen, 2014).

MERCEDES-BENZ STADIUM

Mercedes-Benz Stadium, USA, is a modern, 71,000-seat multipurpose sports arena built to host a range of sports, entertainment and other events throughout the year, including American football, soccer, concerts and other large-scale entertainment events (HOK, 2017). Designed to be a very flexible facility, stadium features a retracting roof system and column-free seating bowl, allowing for the facility to be used for various sporting and entertainment events. The eight-petal retractable roof (Thornton Tomasetti, 2017) is another defining architectural and structural element of the project, operates like the aperture of a camera, and is able to open and close in minutes to offer protection and shade to spectators whilst giving the impression of a floating, gravity-defying roof structure. The roof incorporates ETFE cushions, which reduce the weight of the structure and provide some light transmission, improving environmental performance and creating a light weight roof plane, representing the gravity less architectural approach.

ANALYSIS OF STRUCTURAL PROBLEM AND HOW IT WAS SOLVED

The stadium's **retractable roof** spans approximately **330 m**, creating a fully column-free interior over the seating bowl and concourses. The primary structural challenge was achieving this long-span, movable roof while maintaining stability, minimizing deflection, and ensuring operational safety under variable wind and live loads (Thornton Tomasetti, 2017)

Structural Design Requirements

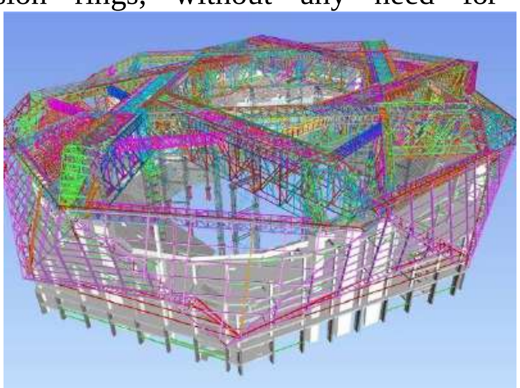
The structural system was developed in response to the following key design criteria:

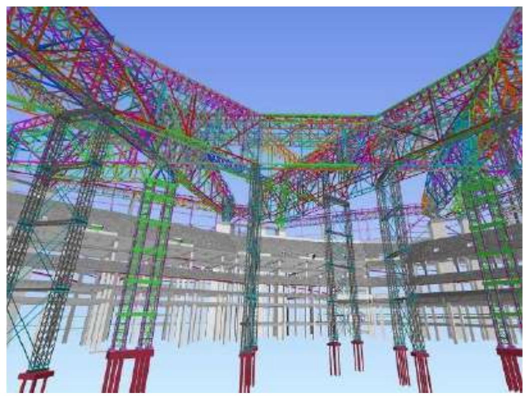
- Column-free, open-plan configuration for unobstructed sightlines and spatial flexibility
- Rapid transformation between open-air and enclosed configurations to support multiple events
- Weather protection and solar shading for spectator comfort
- Lightweight roof structure to minimize loads on the perimeter support system
- Integration of environmental strategies such as daylight control and natural ventilation

These requirements informed a **gravity-less structural strategy**, combining long-span radial trusses with a perimeter compression and tension ring system to redistribute loads efficiently and create the perception of a hovering roof.

SHELL STRUCTURE

Retractable roof has eight triangular "petal" panels, each panel supported by a series of radial trusses that are tied to a central compression ring and a perimeter tension ring. A radial truss is a truss that is used to transfer the vertical and lateral loads from the center over to the outer columns, with a minimum of structural depth. This will allow roof to look visually separated from seating bowl to create gravity-less look. Stability of roof is provided by perimeter compression and tension rings, without any need for internal columns. Precise opening and closing of roof panels with conventional curved rails by means of bogies while maintaining structural alignment. The ETFE cushions lessen dead loads, allow translucency and increase energy efficiency, and the mechanical systems allow for synchronized movement of the roof panels (HOK, 2017; Thornton Tomasetti, 2017).

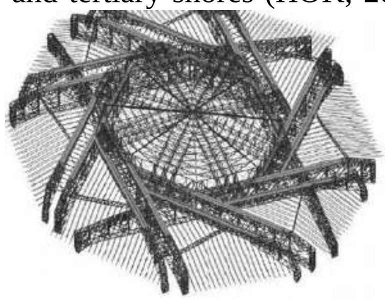


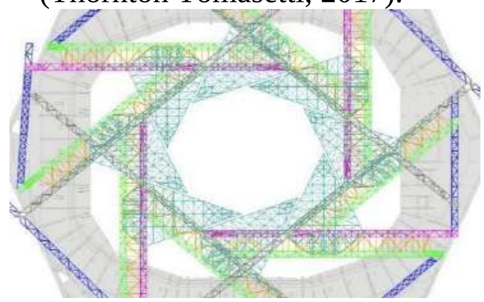


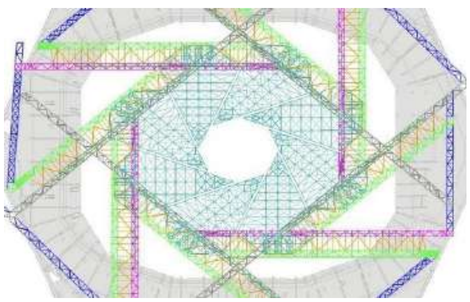
MOVING ROOF

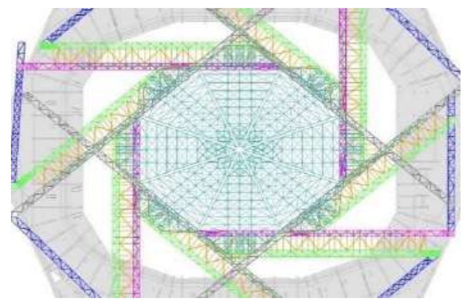
Under retractable petals, fixed roof spans 723 feet and is comprised of 17,000 tons of steel arranged to form a two-way box-truss system with a crisscross pattern of primary and secondary trusses, back-span trusses, and gutter trusses. The roof opening is diagonally spanned by four main trusses, 70 feet deep, with 12 foot top chords, and the inner travel rails for half of the petals are on the top. The remaining petals are supported by four secondary trusses that connect to mega-columns from the primaries (HOK, 2017). There are three roof slope trusses surrounding each petal, from 30' at the base to 4' at the top. Petals vary in length from 196 to 232 ft, in width from 128 to 160 ft, cantilever from primaries 156 ft, overlapping 40 ft (Thornton Tomasetti, 2017). Fixed roof construction was carried out using 13 shoring towers and vertical truss falsework. Fixed roof construction was completed with vertical truss falsework and 13 shoring towers by using crawler cranes. Primary truss was transported on four mega shores, 9 feet deep, 44 to 48 feet in length and 200 feet in height. Four mega shores were used for primary truss; and four for secondary trusses, while five were used for the other steel, known as tertiary shores. Secondary shores were released first followed by primary and tertiary shores (HOK, 2017).

Using a falsework system comprising hydraulic jacks on top of the towers, and a hinged column system which collapsed incrementally, decentering of the roof was achieved. Roof loads were relieved on mega shores and tertiary shores, in a 22-step process, about 1-inch per step (Thornton Tomasetti, 2017).









LOUVERED AREAS

The stadium does not have a louver system like the Singapore National Stadium, but the ETFE roof panels and the surrounding openings serve as environmental control devices, shading, daylighting and natural ventilation. The design enables the stadium to be used in an open air format during good weather to save energy and then fully enclosed when the weather is bad. The design features concourse and community spaces under the roof design which are used for circulation and as points to gather, with social and hospitality spaces underneath. These intermediate spaces promote the interaction and comfort of the public, while mixing circulation, leisure and environmental protection in the building structure. The visually light roof and open, accessible public spaces not only play a vital role in the design's expression but also in its performance (HOK, 2017).

The retractable roof acts as a protection for the environment shielding the spectators from solar heat, rain and wind. The ETFE roof cushions reflect the light of the sun and provide controlled daylight, thereby decreasing the use of mechanical lighting and cooling systems. The roof, when closed, covers the entire seating bowl and concourse to create thermal comfort and flexibility in operation. The combination of kinetic roof movement and the use of lightweight materials shows an example of the integration of structural ingenuity, environmental performance, and architectural expression in a gravity-less design strategy (Thornton Tomasetti, 2017).

COMPARISON AND DISCUSSION: GRAVITY-LESS ROOF STRUCTURES:

A glass ceiling designed to be more transparent and visually more flexible than steel is characteristic of the new roof of the Singapore National Stadium and Mercedes-Benz Stadium.The roofs of the Singapore National Stadium and Mercedes-Benz Stadium are both gravity-less and innovative, offering long spans, column-free interiors and combining environmental and functional performance. The roof uses a continuous shell construction with primary and secondary arches supported by a tension ring along the perimeter of the roof to form a stable structure with an unobstructed view and flexibility for various sports. It features retractable panels and louvers on the concourse which allow it to shade, protect from the rain and also permit passive cooling, highlighting its robust functioning and being environmentally responsive. Somewhat in contrast, Mercedes-Benz Stadium has an eight-petal kinetic roof that is held up by radially connected trusses, which extend from a central compression ring to perimeter tension rings. The lightweight ETFE cushions lower the structural load, improve daylighting and provide the impression of a floating roof, and the kinetic petal system enables quick opening and closing to suit event set-ups. Both projects showcase the gravity-less approach to architecture in their structural ingenuity and material optimization, but Singapore's project focuses on shell continuity and passive environmental control, while Atlanta's project focuses on dynamic movement, the creation of visual spectacle and quick changeability. These case studies demonstrate that gravity-less design is not just a solution for long span roofs, but also a tool for defining architectural expression, environmental performance and user experience in modern st adium buildings, as engineering and design take a more prominent role in their design.

Feature / Parameter	**Singapore National Stadium**	**Mercedes-Benz Stadium, Atlanta**
Seating Capacity	55,000	71,000
Roof Type	Free-span dome with movable panels	Eight-petal retractable roof
Structural System	Primary and secondary arches + pre-stressed perimeter tension ring	Radial trusses connected to central compression and perimeter tension rings
Column-Free Interior	Yes	Yes
Span Length	312 m	330 m
Movable Roof Mechanism	Two large panels sliding along runway beams	Eight petals opening like a camera aperture
Roof Material	ETFE panels + aluminum-reflective panels	ETFE cushions
Environmental Control	Louvers, air-cooling system, shading	ETFE translucency, perimeter openings, natural ventilation
Design Emphasis	Shell continuity, adaptability,	Kinetic motion, visual spectacle,

Feature / Parameter	**Singapore National Stadium**	**Mercedes-Benz Stadium, Atlanta**
	passive environmental control	rapid transformation
Gravity-less Effect	Achieved via shell action and load distribution	Achieved via radial trusses and lightweight petals

CONCLUSION AND LESSONS LEARNED

The Singapore National Stadium and Mercedes-Benz Stadium are compared to show the various facets of gravity-less roof design in modern stadium design. The contrasting approaches reveal that both projects use innovative structural strategies, with varying degrees of success, to secure column-free interiors: Singapore adopts a philosophy of shell continuity, interlocking arches, and a pre-stressed perimeter ring to achieve structural stability, adaptability, and passive environmental control, while Atlanta is based on the idea of radial trusses and kinetic, eight-petal retractable panels to create a visually dynamic, rapidly transformable roof. The above case studies clearly show that gravity-less design is not only a structural answer but also a catalyst to architectural expression and environmental responsiveness and user experience.

Key lessons learned from these projects include:

- Integration of Structure and Architecture: Gravity-less design requires a seamless relationship between structural systems and architectural form to achieve both stability and aesthetic impact.
- Material Optimization: Lightweight materials such as ETFE play a critical role in reducing structural loads while enhancing translucency and environmental performance.
- Kinetics and Adaptability: Incorporating movement in roof systems can expand functional flexibility and create visually striking forms but requires precise engineering and synchronization.
- Environmental Performance: Roof geometry, shading systems, and ventilation strategies can be integrated within structural frameworks to mitigate climatic challenges without compromising architectural vision.
- Context-Driven Design: Structural strategies should respond to programmatic needs, site conditions, and cultural expectations; continuous shell systems favor robustness and multi-sport adaptability, whereas kinetic petal systems emphasize spectacle and rapid transformation.

Overall, these stadiums exemplify how gravity-less design can push the boundaries of engineering and architecture, demonstrating that long-span roofs can simultaneously achieve structural efficiency, environmental sustainability, and iconic spatial experiences.

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