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RESEARCH ARTICLE

Evaluation of Structurally Integrated Surface Articulation (SISA) Panels for Architectural Engineering Applications

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ABSTRACT

This research explores the efficiency of a newly developed Structurally Integrated Surface Articulation (SISA) system for a variety of structural engineering applications, such as exterior building facades and solar panels. SISA is a modular system that consists of dynamically adjustable three-dimensional surface panels supported by an internal wire-frame space structure. The articulation techniques vary depending on the specific function of the panels, with configurations designed to optimize structural performance through composite action between the outer surface panels and the internal frame. Materials such as plastic, smart glass, and sheet metal are evaluated in conjunction with polyhedral and honeycomb configurations, including tetrahedral and convex polygonal forms. The research emphasizes enhancing large-scale structural efficiency by integrating modern frame systems with surface articulation. It also explores the evolution of architectural design and presents case studies using SISA-based structures to highlight the potential improvements in structural integrity. By addressing both material properties and design techniques, the study aims to demonstrate how the SISA system can provide significant advancements in architectural engineering.

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1. INTRODUCTION

The roles and functions of architecture have evolved with the global rise of architects and engineers, leading to the development of new "Generic Building Types." Architectural concepts traditionally address three key challenges: providing protection, ensuring durability through materials and gravity, and creating aesthetic beauty [1]. Design involves three main elements: horizontal and vertical subdivisions and the balanced grouping of masses [2]. In modern architecture, particularly under the High-Tech trend, traditional configurations are being replaced. Imagining and recording spatial configurations have become key activities that differentiate architects and engineers from other building planners [3]. Modern constraints demand innovative structural solutions, making composite materials and optimized configurations increasingly relevant. Understanding historical architectural developments can provide valuable insights for contemporary design challenges.

More rigid methods are needed to address the design problems of today, therefore improving composite structures is essential to finding complete and efficient solutions. Architectural practices have changed throughout time and comprehending them now requires looking at pertinent historical instances and arrangements. Severe weather, earthquakes, and other environmental pressures pose a constant hazard to buildings, which frequently necessitates ongoing damage and repair. The ground-breaking "Generic Building Type" offers novel ideas for the fabrication, assembly, and installation of building components while being resilient enough to withstand natural disasters. This approach may increase both short-term cost-effectiveness and long-term economic gains by utilizing local labour resources. Technological developments offer a variety of intriguing ideas for contemporary architectural and technical building kinds. The true challenge is embracing these innovative, forward-thinking ideas and eschewing the outdated, inflexible industrial methods.

Not only are planning and designing essential to surroundings today, but they also place a strong emphasis on modernism, artistry, and aesthetics. In order to sustain and retain ground loads, the new generic building type takes into account both geometric strength and deformation ability. Lightweight structural frameworks by interstitial composite panels are one way to accomplish this purpose. Because these systems are prefabricated, considerable energy savings are possible, and the buildings can endure environmental stressors like tornadoes. The system includes an earth cover supported by a low-profile, double-envelope, clear-span space frame. The term "structural articulation" describes how the fragmentation of form and face divides huge, heavy sections or concentrated blocks into human-sized components.

This article presents examples supported by a literature review and offers a case study of a project designed by SISA. Within the framework of structural analysis and engineering principles, the study examines the performance of large-span structural systems, evaluating innovative solutions of SISA in the context of project design. The work addresses applications aimed at improving structural efficiency from both theoretical and practical perspectives, with a focus on architectural engineering approaches.

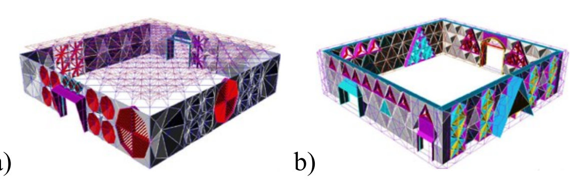
2. A NEW GENERIC METAL BUILDING TYPE: STRUCTURALLY INTEGRATED SURFACE ARTICULATION (SISA)

Using standard components, SISA is designed to be a "Generic Building System and Technology," enabling the implementation of many configurations, permutations, and combinations of structural engineering applications to encompass a wide range of specific and multipurpose functions. SISA is a modular system comprising three spaces and articulated, geometrically distorted sheet metal and sheet plastic surface panels. Unlike traditional two-dimensional surface systems that are added to an existing steel superstructure, this system combines surface and structural integration from the start, removing the need for separate massive structures and applied dead loads. Moreover, stiff structural foam may be laminated or otherwise connected to these surface panels to improve the structural qualities of the panel configuration through composite action.

Using the exponential structural benefit of surface deformation and geometric configuration, SISA integrates "Façade and Structure" into a single, harmonious module. SISA is an exceptionally strong weight system, each of whose parts can be set up to work in concert with one another to enable single-unit characteristics in response to be dividing static and dynamic stresses. SISA adds dead-load stress to a pre-erected structural system; it is not an independent cladding system.

The SISA system introduces innovative concepts for high-rise buildings, utilizing "fractal" and "honeycomb" patterns within an ultra-light space frame. This approach allows for the construction of very tall buildings with minimal heavy steel or concrete, potentially using only modified front-end loaders for assembly. This cutting-edge, high-tech approach offers significant economic benefits and advancements in urban development. SISA can be applied from the exterior in deep, linear, inter-panel pockets, formed along each panel edge.

Fig. 1 show the SISA configurations inspired by algorithms and geometric constraints. The design focus on the maximal surface with multi-dimensional symmetries to create continuous honeycomb surfaces which are highly expandable.



a) b)

Figure 1. a) The SISA design uses triangular disphenoid form b) The form design octagonal disphenoid honeycomb.

3. EXPLORING THEORETICAL FRAMEWORKS OF SISA IN CONTEMPORARY BUILDING DESIGN

The method of articulation influences the design of joints in architectural projects, affecting how shapes, dimensions, scales, ratios, and visual weight are perceived. The contrast between the colour of the surface and its surroundings impacts the tonal value and visual effects of the design. In modern structural architecture, articulation refers to the design of joints between formal elements using patterns, colours, textures, tones, forms, shapes, and lines within structural design. Each section of a work is connected through these joints, ensuring that individual pieces fit cohesively into the overall composition [4]. Modern architectural perspectives on articulation focus on creating iconic structures. This concept applies to structural and engineering elements, as well as enclosure elements like wall systems and construction techniques [5].

Articulation can be defined through some key steps: differentiating adjacent surfaces by varying materials, colours, designs, and aesthetics. Each part features unique linear elements that are separated by adjacent planes, and removing corners can define boundary planes. The way light interacts with the form helps in creating distinctive shapes and emphasizes sharp contrasts in tonal values along edges and corners [4]. Integrating these elements externally enhances the exterior aesthetics of the building while keeping the interiors open and versatile for design and functionality. The goal of SISA is to create an environmentally friendly, low-impact, semi-autonomous ecosystem with high-tech attributes that complement form, function, and long-term economic viability, representing a new architectural paradigm for megacities.

In the provided examples of related configurations, multiple lattice systems are layered. A given topology can be supported additively from within the shell or through a combination of both methods, depending on specific load requirements. Beyond basic shapes like cubes, cylinders, and cones, the use of generic space-frame systems can be extended to create shell structures with limited or complex surface geometries. Lattice and diaphragm combinations can be designed into large, transportable multi-panel modules for sequential field assembly. Additionally, flexible truss lattice systems are ideal for quick assembly and welding, making them suitable for large spaces like botanical conservatories, particularly in double-envelope designs that provide plenum without the need for ductwork. The structural benefits of surface deformation are evident in many everyday objects, such as steel or plastic panels and modular corrugated siding. Modern, high-tech prototypes are not only acceptable but often preferred. In rural areas of China, India, Pakistan, Mexico, South America, Africa, and parts of rural America, conventional metal building types are prevalent [6].

SISA aims to develop modular components for:

- Innovative metal building designs featuring three-dimensional structural systems.
- High-strength canopies suitable for various applications such as festival halls, market structures, covered walkways, and pedestrian bridges.
- Space applications, including solar collectors and reflectors for energy transmission to Earth.
- Conservatory structures, using sheet metal instead of glass as a diaphragm for purposes such as field hospitals, modular housing, aviaries, butterfly houses, gazebos, pavilions, and outdoor furniture.

3.1. Theoretical Building Science with SISA

3.1.1 House systems

SISA system offers innovative solutions for modern housing systems through modular sheet components. This approach integrates three-dimensional structural frameworks, enhancing both functionality and aesthetics. This research has highlighted the potential of SISA in creating durable and versatile residential environments, benefiting from its efficient use of materials and ability to withstand environmental stresses.

One significant advantage of SISA in residential applications is its adaptability to different building types and climates. For instance, its use in modular housing allows for rapid assembly and customization, which can be particularly beneficial in areas with limited construction resources or in emergency situations [7]. Additionally, the components of SISA offer robust solutions for creating energy-efficient and environmentally friendly homes [8].

Figure 2 below illustrates the Desert Wing House, designed on a three-acre plot, where the structure features a combination of rammed earth formed into brick-like shapes or layered rows [9]. The design focuses on integrating walls and large glass surfaces to capture scenic desert views. The articulation is evident through the interplay of glass, walls, and roof, all forming a unified small building concept.

Figure 2. Desert Wing [10].

3.1.2. Structural systems for expansive span frames

Designing expansive span frames necessitates advanced structural systems capable of addressing the complexities of large-scale projects. The approach of SISA leverages modular and lightweight strategies to integrate cutting-edge materials and construction techniques, resulting in strong, adaptable, and economically efficient structures. The significance of modular construction in contemporary architectural practices, particularly for extensive span systems [11]. By employing space frame systems, SISA optimises load distribution and reduces reliance on heavy materials, thereby strengthening structural performance. Additionally, this method promotes sustainability through the use of prefabricated components, which helps decrease environmental impact and shorten construction periods.

Structures subjected to compression loads generally exhibit reduced efficiency compared to those under tension loads. While tension structures typically fail through material yielding, compression structures are prone to buckling before material failure occurs [12]. The system can include tessellated, arched, and folded-plate configurations, employing single curvature combined with geometric strength or compound curvature with enhanced geometric support.

Figure 3 illustrates the Heydar Aliyev Cultural Centre, which was designed to become a central symbol of the cultural identity of the nature. The design of it fosters a seamless, fluid connection between its surrounding plaza and the interior of the building [13]. This project serves as a prominent example of expansive span architecture, integrating a fluid frame system that interacts dynamically with various interior levels.

Figure 3. Heyder Aliyev Cultural Centre, Azerbaijan [14].

3.1.3. Structural systems for expansive span frames

Adaptive use voids are being integrated into all spaces, with SISA systems employed as cladding. Honeycomb structures, which are frequently found in nature, offer notable strength, rigidity, and lightness. These properties make them suitable for diverse applications, including satellite components.

Advanced structural systems are essential for the design of high-rise buildings, particularly when incorporating innovative strategies such as those developed by SISA. The approach of SISA utilizes modular and lightweight components to improve the performance and efficiency of tall structures. Modular construction is crucial for addressing the complexities of high-rise projects, offering both adaptability and strength [8,15]. The systems of SISA employ space frames and advanced materials to provide effective load distribution, reducing reliance on traditional, heavy construction materials. This methodology not only enhances structural integrity but also promotes sustainability by minimizing environmental impact and shortening construction time through the use of prefabricated and plant-based materials [16]. Modern high-rise designs benefit from structural systems that integrate geometric principles with material properties to optimize performance under various loads [17]. Adopting concepts of the SISA represents a significant advancement in high-rise construction, fulfilling contemporary demands for efficiency and environmental sustainability.

Figure 4 illustrates the Origami Building, which features a prominent glass façade complemented by a secondary layer of screen-printed marble patterns. This design creates an origami-like effect, visible both from inside and outside the building [18]. The façade employs layered curtain panels arranged in a fractal honeycomb pattern, enhancing the exterior of the building. The sophisticated building system manages shading through a complex façade algorithm, optimizing light control and aesthetic impact.

Figure 4. Origami Office Building [19].

3.2. Relationship Between Structure and SISA

The relationship between structural systems and architectural design has seen significant evolution, especially with innovative approaches such as those employed by SISA. This relationship emphasizes the crucial interplay between structural efficiency and aesthetic design, demonstrating how modern architectural advancements can seamlessly integrate with robust engineering principles [20].

Surface Articulation and Structural Integration

Surface articulation involves the careful design and placement of a surface elements of the building to enhance both its visual appeal and functional performance. In terms of structural systems, this entails using materials and geometric configurations strategically to achieve desired visual and structural effects [20-21].

The Approach of SISA to Structural and Architectural Integration

The methods of SISA illustrate this integration by using modular and lightweight structural elements that complement advanced architectural designs. For instance, the Hearst Tower of Norman Foster utilizes a triangulated diagrid structure that reduces steel frame usage by 20% compared to conventional designs (Fig. 5). This not only boosts structural efficiency but also enhances the unique aesthetic of the building, contributing to its overall identity. The design of the building, inspired by origami, exemplifies how surface articulation can be used to create complex, visually engaging forms while maintaining structural stability [20,22].

Figure 5. Hearts Tower [23].

Implications for Modern High-Tech Architecture

The approach of SISA, combined with contemporary high-tech architecture, shows how structural systems and architectural design can work together to meet both functional and aesthetic requirements. By utilizing modular construction, space frames, and cutting-edge materials, SISA addresses current needs for efficiency, sustainability, and visual impact [20,24]. This collaboration underscores the importance of ongoing interaction between engineers and architects to advance building design.

In conclusion, the interaction between structural systems and surface articulation, as demonstrated by SISA and modern high-tech projects, reflects the changing landscape of architectural design. This integration not only progresses the field of architecture but also contributes to the creation of more efficient, sustainable, and visually impressive buildings [25].

4. METHODOLGY

The SISA methodology, particularly in modular architecture, integrates advanced surface articulation techniques that emphasise both functionality and aesthetic value. Fig. 6 demonstrates how the various components of the proposed SISA align with and contribute to achievement of the research objectives. Modular building design aims to create a balance between urban picturesque and high-modern architectural themes. Industrial materials such as steel and smart glass are often used to enhance the strength and durability of modular structures improve both the visual impact and structural efficiency of these buildings [26].

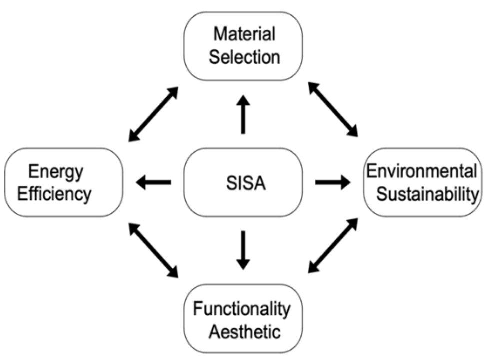


Figure 6. The research methodology adopted for the study of the SISA structures.

In SISA, the selection of materials is paramount to ensuring structural resilience, environmental sustainability, and resource efficiency. Practitioners of modular architecture focus on materials that reduce the environmental footprint while maintaining long-term availability, such as recyclable glass or low-impact materials [26-28]. While sheet metal and aluminium are common for surface grids, the design flexibility of modular systems allows for the integration of alternative materials, depending on project-specific requirements and cost-efficiency considerations [29].

The use of surface articulation techniques, such as tessellated or folded-plate geometries, further enhances both structural integrity and energy efficiency. These configurations optimise load distribution, maximising strength while reducing material use. In addition, they contribute to thermal efficiency, as the façade interacts with environmental conditions to regulate internal temperature, minimising the need for artificial heating and cooling systems.

Semi-autonomous energy management is also a core feature of the SISA methodology, achieved through innovative double-envelope systems. These systems, constructed using glass and plastic, reduce overheating by facilitating passive ventilation during cooling cycles and trapping heat during heating cycles. Airflow is strategically routed through sub-floor and ceiling plenums, enabling radiant heating and cooling. This energy-efficient approach is often supplemented by renewable technologies like solar, wind, and geothermal systems, aligning with the emphasis of SISA on sustainability.

In conclusion, the integration of SISA of surface articulation and modular design leads to high-performance, energy-efficient structures that are not only visually striking but also functionally resilient. The methodology exemplifies the balance between structural innovation and environmental responsibility, setting a precedent for modern sustainable architecture.

4.1. Frame Geometry

Whether functioning as edges and interstitial spaces acting as diaphragms in folded plate systems or as struts with empty interstitial spaces in space-frame systems, these elements offer a method to investigate and analyse plate and frame structures. Structural components utilizing folded plate and space frame systems for universal structural applications derive from developable or para-developable surface configurations. These configurations allow for the breakdown of surfaces into parts suitable for fabrication and assembly. Specific methods of joining components in structural and volumetric arrays permit precise alignment in positive or negative fold positions, and enable the determination of rectilinear, curvilinear, and skewed surfaces, along with the enclosure of amorphous volumes.

The interest in space frame structures has been invigorated by new structural forms. Space frames exhibit significant structural capacity and visual appeal and are used for both long-span and mid- to short-span enclosures. The geometry of the space frame offers several advantages, including suitability for various surfaces, high static strength, lightweight construction, lower production costs, mass production in factories, and flexibility in the positioning of numerous members in space. Space frames can be formed with either planar or curved surfaces.

The mechanism of SISA involves four distinct combinations of layers:

- **Primary:** Space-frame grid structures
- **Secondary:** Internal and external grids; dual and complementary
- **Interstitial:** Internal and external lattices
- **Unit Structural Closure:** A complete space frame determines a honeycomb of tetrahedral components.

The most crucial aspect is that tetrahedral closure and unit stability are determined upon the completion of the wireframe and space frame structure, independent of additional interstitial surface panels or shell components. However, the inclusion of shell surface components in their composite configuration significantly enhances the strength characteristics of the unit system.

4.1.1. Space frame structures

Space-frame structures employ a three-dimensional grid of interconnected elements to create a lightweight and robust framework, as shown in Fig. 7. This design efficiently distributes loads, enhancing the overall strength and stability of the structure while minimising material use [30]. The spatial grid design optimises material efficiency and cost by effectively distributing forces across the framework. This adaptability allows spaceframes to accommodate a wide range of architectural forms, from simple to complex, making them ideal for large-span roofs and intricate façades. Additionally, the open grid structure imparts a contemporary and visually striking aesthetic, enhancing the overall appearance of the building [31]. Spaceframes are particularly suited for expansive structures like sports facilities and exhibition centres and integrate well with elements such as glass façades, combining functionality with visual appeal. Precision in fabrication and assembly is crucial to maintain structural integrity, with technological advancements improving the efficiency and practicality of constructing these frameworks [32].

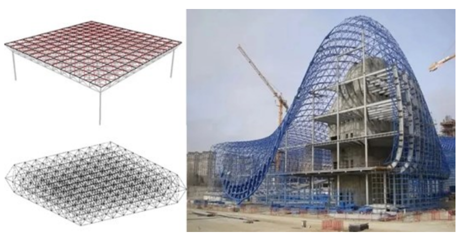


Figure 7. The space-frame Structure in Heydar Aliyev Centre [30].

4.1.2. Space grid structures

The geometry of space grids plays a crucial role in structural engineering by distributing mechanical loads effectively across a network of interconnected elements. Space grid structures can support substantial mechanical loads due to their dense, multi-layered configurations [33], as shown in Fig. 8. These designs incorporate various geometric forms, such as triangular, orthogonal, and tetrahedral shapes, alongside different fabrication techniques. The versatility in materials and geometry allows for numerous variations in joint configurations, optimizing strength, length, and transportability [29].

The dimensions of space grids are influenced by multiple factors, including span height, face shape, building planes, and joint costs. The repetitive nature of space grid elements simplifies fabrication and assembly, enhancing efficiency and reducing complexity [33]. For instance, triangulated grids create continuous, straight edges, while pentahedron units offer substantial coverage and stability. The continuous inward and outward joints around each combined tetrahedron further contribute to the structural integrity and flexibility of the grid system.

These space grids can be visualized through examples such as those involving tetrahedrons and pentahedrons, which are designed to form a network of interconnected units. This design approach simplifies the creation of large, continuous structures while maintaining structural efficiency and aesthetic appeal [29,34].

Figure 8. The space-grade structure in Eden Project, Cornwall UK.

4.1.3. Lattice grid structures

Lattice grid structures are highly regarded in structural engineering for their efficiency and adaptability. These systems employ a three-dimensional network of interconnected members that form a grid-like framework. The lattice grid excels at distributing mechanical loads across the structure, thereby optimizing material usage and reducing overall construction costs. The design of lattice grids supports various geometric configurations, including triangular, orthogonal, and tetrahedral forms [29,31,35]. This versatility accommodates different fabrication techniques and material options, such as aluminium, steel, and plastics.

The lattice grid design facilitates straightforward manufacturing by using repetitive elements, which streamlines both the production and assembly processes. The adaptability of lattice grids allows for modifications in span heights and face geometries, making them suitable for diverse architectural applications, including large-span roofs and intricate facades. The design of the system also allows for a range of joint configurations, which enhances structural strength and durability [36]. This approach to surface articulation effectively balances structural integrity with aesthetic considerations, ensuring both functional and visual effectiveness in complex architectural designs.

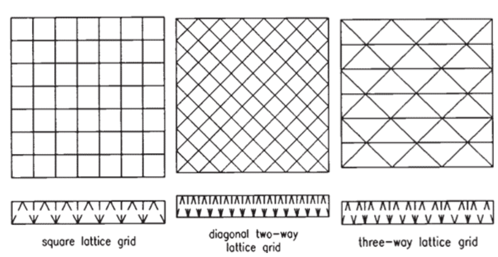


Figure 9. The examples of lattice grid space structures [37].

4.2. Materials of SISA

4.2.1. Sheet Metal

Sheet metal is widely used in structural and architectural engineering due to its adaptability, strength, and cost-effectiveness. It is formed by rolling the metal into thin, flat pieces, easily manipulated through bending, cutting, and forming. These characteristics make sheet metal an ideal choice for both functional and aesthetic applications in construction. The ability to fabricate sheet metal into complex shapes using stamping, deep drawing, and hydroforming techniques has extended its use beyond simple structural elements to more intricate architectural forms. In addition to its formability, the strength-to-weight ratio of sheet metal makes it essential in applications requiring lightweight yet durable materials. Table 1 and Fig. 10 shows the details of sheet metal forming process [38].

Table 1. Sheet Metal Forming Work Step [39].

Properties
A metal sheet is cut from a stock material to produce individual blanks.
The blanks are placed between two tools in a forming machine.
Significant forces from the machine act on the metal sheet.
The upper die (punch) applies pressure, shaping the metal around the lower die.

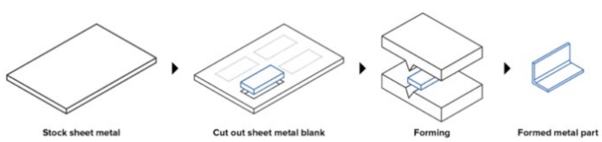


Figure 10. Process workflow for sheet metal forming [39].

Its composition includes a variety of metals, such as aluminium for corrosion resistance, steel for high strength, and stainless steel for enhanced durability and resistance to oxidation. This versatility allows sheet metal to be used in building facades, roofing, and cladding, where both aesthetic quality and long-term performance are critical. In the field of surface articulation, the thinness of sheet metal allows for precise manipulation of the surface, creating complex patterns or articulations that enhance both structural and aesthetic performance [38,40].

The sheet metal is integral in achieving optimal load-bearing properties when used in conjunction with other materials, such as in composite systems where it contributes to the overall stiffness and strength. For example, in honeycomb or lattice configurations, sheet metal adds to the rigidity of the structure while maintaining a lightweight profile, making it suitable for large-span architectural applications. Moreover, its capacity to be recycled and repurposed aligns with modern sustainability goals in engineering, further cementing its role in the future of construction materials [38,40,41].

4.2.2. Glass

Glass is extensively utilized in construction due to its array of benefits, including transparency, chemical resistance, environmental sustainability, durability, accessibility, minimal maintenance, recyclability, and cost-efficiency [42]. In the realm of construction, glass serves various functions, from enhancing aesthetic appeal to improving energy performance. Its properties make it a fundamental material in modern architecture, where buildings without glass facades or windows are virtually inconceivable [43]. Figure 11 illustrates several typical uses of glass in building structures.

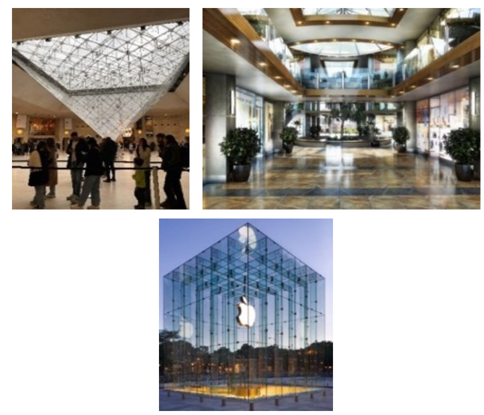


Figure 11. Examples of modern buildings that are using glass for aesthetics, lighting, and more space, etc. [42].

The float glass process, developed by Pilkington in 1959, is used to produce high-quality flat glass efficiently, eliminating the need for extensive finishing processes [44]. This method dominates the glass market, accounting for over 80-85% of glass used in construction. Float glass is commonly used in the building industry for structural window glazing, contributing to well-lit and spacious buildings.

Annealed glass is primarily produced using the float process. In this method, raw materials are mixed and melted in a furnace at approximately 1500°C, creating a molten tin bath. The molten glass is continuously poured onto the tin bath at around 1000°C and gradually cooled to 600°C. During this cooling phase, the glass is drawn over rollers before entering a lengthy annealing furnace (Fig. 12). Tin remains stable in a liquid state at 600°C, allowing glass to float on it. Controlled cooling, or annealing, at the end of the tin bath, ensures a gradual reduction in temperature, which helps to prevent residual stresses. Glass thickness, ranging from 2 to 22 mm, is managed by adjusting the roller speed through the annealing lehr. The glass is then cut into large sheets measuring 3 m × 6 m before being stored. Adjustments in roller speed impact glass thickness and vice versa [42-45].

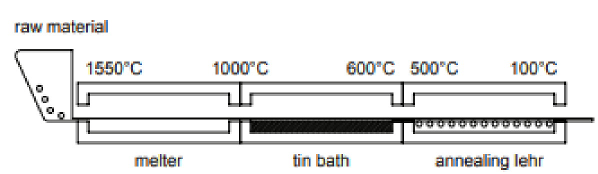


Figure 12. Float glass production process [44].

4.2.3. Plastic

The growing use of plastic materials in construction and engineering projects plays a significant role in the pursuit of efficiency and creativity in modern architecture [46]. This approach aligns with the core principles of SISA, which embraces a design philosophy that balances functionality, aesthetics, and technology in structures. Plastic stands out as a versatile and flexible material employed by engineers and architects to achieve this balance.

With its lightweight nature, design flexibility, and recyclability, plastic complements SISA principles of sustainable and innovative building solutions. For example, plastic materials like PVC and polyethene are used in modern buildings for windows and flooring, providing both durability and energy efficiency [46-48]. According to SISA principles of innovation and high-tech integrated design, plastic materials offer architects and engineers unlimited design possibilities while supporting modern building designs without compromising structural performance.

Plastic meets SISA functional and aesthetic expectations, while also contributing to cost reduction and long-term performance in engineering processes. Additionally, the reusability and recyclability of plastic materials reinforce SISA commitment to environmental sustainability. Structures built using plastic materials offer energy-saving and eco-friendly structural solutions. Plastic, which aligns with SISA innovative design philosophy, merges functionality and aesthetics in both architectural and engineering processes [49]. Fig. 13 below shows a housing complex in Poland designed by Moomoo Architects. The building features Thermopian, an insulating plastic typically used for roofing, applied entirely to the facade. Completed in 2008 in Lodz, the 200 m² structure combines traditional Polish house proportions with a modern, minimalist approach [50].

Figure 13. L House Poland [50].

4.2.4. Aluminium

Aluminium, a nonferrous metal, is extensively utilized in both its pure form and as an alloy across various industrial sectors due to its ease of fabrication and low maintenance needs. Its malleability allows for effortless pressing and shaping, making it suitable for a wide range of applications. The resistance of the aluminium to corrosion and superior thermal properties enhances its effectiveness in exterior applications. Key attributes include a high strength-to-weight ratio and excellent conductivity, which contribute to its use in residential buildings, automobiles, aircraft, and electronic devices [51-53].

In the context of SISA, aluminium aligns well with the principles of combining functionality, aesthetics, and advanced technology. SISA focuses on integrating innovative materials to improve structural performance and design efficiency. The high ultimate tensile strength and versatility of aluminium, especially in extrusions and flat-rolled sheet plates, support the creation of durable and efficient structures. Using aluminium in SISA-based designs enables engineers and architects to achieve both structural integrity and aesthetic flexibility, adhering to contemporary architectural and engineering standards and the versatility of aluminium, allowing for effective incorporation into structural designs. This process helps achieve reduced loads and extends the service life of structural components, making aluminium a valuable material in modern engineering and construction.

5. CHARACTERISATION AND ANALYSIS OF SISA FACE TYPES IN STRUCTURAL APPLICATIONS

In the design of SISA facades, there is an extensive range of configuration possibilities. The theory behind this is provided by examples of various façade edge cells, including disphenoid, disphenoid tetrahedral honeycomb, convex uniform honeycomb, and the frequently used tetrahedron. Designing an innovative façade involves a creative process that integrates perspective vision and the consideration of different image layers within the building.

5.1. Frame Geometry

Incorporating provided materials into these designs offers significant benefits due to its versatility and adaptability. The extrusion process enhances the ability of the aluminium to be shaped into diverse forms, which aligns well with the innovative configurations discussed. The properties of aluminium support the creation of complex façade designs while maintaining structural integrity and aesthetic appeal. Its application in SISA facades allows for the realisation of intricate and visually striking building envelopes that meet both functional and design objectives.

5.1.1. Disphenoid

The disphenoid is defined as a wedge-shaped crystal form in the tetragonal or orthorhombic system, characterised by four triangular faces that alternate with the faces of a tetragonal or orthorhombic dipyramid. This shape is symmetrical about three mutually perpendicular diad axes in all classes except the tetragonal-disphenoid, where an inverse tetrad axis of symmetry generates the form [54]. In a disphenoid, all edges are of equal length, and any third component measurement exceeds the square of the first and second components squared [55]. The vertex angle of any disphenoid is equal to two right angles, though the edges may vary in separation. To construct a disphenoid, one must cut out the shape from a triangular plane and fold it through the midpoints of its lengths [56].

Figure 14 illustrates disphenoid configurations created by combining three tetrahedra that share faces. In this structure, the edges of the disphenoid form pairs of symmetrical configurations where two adjacent cells interconnect. Each vertex of the disphenoid is identical, and the sum of the face angles at each vertex totals two right angles. Additionally, all faces of the disphenoid are congruent, with triangles arranged in a specific pattern. By integrating disphenoid patterns into SISA designs, aesthetically pleasing structures can be achieved complex that leverage the geometric precision and strength inherent in these configurations.

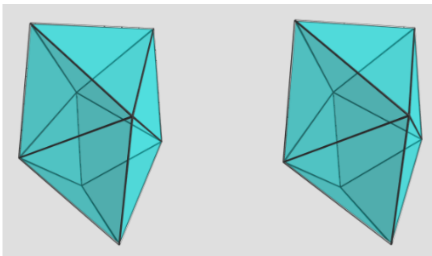


Figure 14. The disphenoid configuration that combines a tetragonal and orthorhombic dipyramid [57].

5.1.2. Tetrahedral disphenoid honeycomb

This configuration represents a space-filling tessellation comprised of identical tetragonal disphenoid cells, each defined by four isosceles triangle faces. The arrangement of these cells forms a lattice that mimics the structure of a body-centred cubic lattice, enabling both efficient space usage and enhanced structural stability. The tetrahedral disphenoid honeycomb, specifically, is characterized by its surface covered with a honeycomb pattern, where each cell has a transitional plane with four identical triangular faces [58]. The cells in this configuration can be subdivided through their central edges, resulting in a pattern where two faces and two sides align vertically.

Figure 17 illustrates the uniform tessellation in three-dimensional space, where the cells consist of pairs of identical isosceles triangular faces. Each edge of the tetrahedral disphenoid is enclosed by this tessellation. A cell is situated with central points that connect pairs of triangular faces, extending through the centre points of the corners, edge vertices, and face centres.

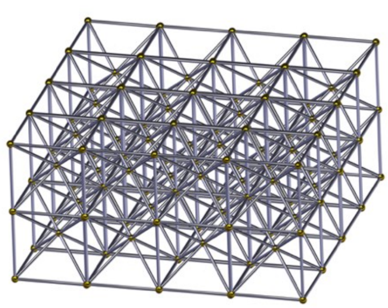


Figure 15. The tetrahedral disphenoid honeycomb configuration [58].

5.1.3. Tetrahedron

A tetrahedron is a polyhedron consisting of four triangular faces, each meeting at a common vertex. This geometric shape can be folded from a single piece of flat material, such as paper, creating a sturdy structure [59]. On a conventional plane, the architectural faces of a tetrahedron are not typically prioritised for placement. However, tetrahedral diagrams provide insight into the folding parameters, which are integral to its form. Tetrahedron, known for their elegance and flexibility, are often applied in layers to achieve aesthetically pleasing designs [60].

Figure 16 below presents a pavilion in Montreal, Canada, where the roof is composed of tetrahedral pyramids of varying sizes. The design utilises a tetragonal framework, serving as a prototype for new construction methods. By relying on a single folded system, the structure avoids the need for additional complex components.

Figure 16. The Canadian Government Pavilion at Expo '67 in Montreal [61].

5.1.3. Octahedron

An octahedron is a polyhedral shape characterized by eight triangular faces, twelve edges, and six vertices [62]. This geometric structure has been applied in architectural design due to its mathematical symmetry and capacity to form stable frameworks. Octahedral configurations are frequently employed in lightweight construction materials, such as honeycomb structures, owing to their ability to distribute loads efficiently. These shapes often serve as integral elements in spaceframe systems, where they provide structural rigidity while maintaining a low weight-to-strength ratio [29]. Octahedral lattice system is frequently used in spaceframe designs, as illustrated in Figure 20. These systems allow for the assembly of strong, self-supporting frameworks, which can be easily transformed, dismantled, and rebuilt.

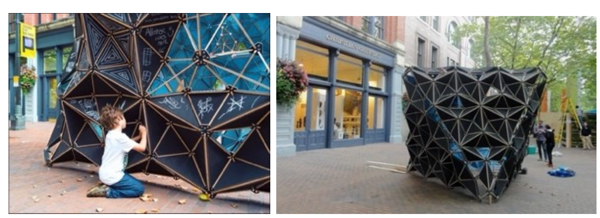


Figure 17. The Octahedron pavilion by LMNTechStudio [63].

5.2. The Advantages of Geometric Shapes in SISA

The geometric shapes presented above offer significant potential for enhancing structural integration and performance. Each of these shapes presents various advantages in SISA:

- **Disphenoid:** In the context of SISA, the disphenoid shape enhances both lightness and durability within structural frameworks. Its capacity to provide superior stability under diverse loads is particularly beneficial for integrating components into complex systems, ensuring efficient and resilient structural performance.

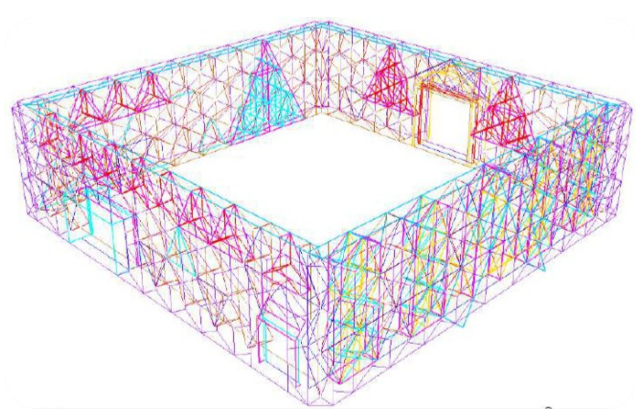
- **Tetrahedral Disphenoid Honeycomb:** The tetrahedral disphenoid honeycomb structure is highly advantageous for SISA applications, offering an excellent weight-to-strength ratio and substantial rigidity. Its lightweight yet robust nature makes it ideal for incorporating into advanced structural systems, while its optimal use of internal voids contributes to enhanced performance and structural integrity.

- **Tetrahedron:** Within SISA frameworks, the tetrahedron is recognised for significantly improving structural strength and stability. Its ability to provide effective support under varied loading conditions makes it a versatile component in architectural designs, facilitating flexible and robust structural solutions.

- **Octahedron:** The symmetrical and balanced structure of the octahedron is highly beneficial in SISA, addressing various engineering challenges with its inherent durability and aesthetic appeal. This geometric shape enhances the overall efficiency and visual impact of integrated structural systems, offering both functional and design advantages.

6. A COMPLEX STRUCTURE ENGINEERED USING SISA

The figures presented illustrate a conceptual design developed through SISA. The design incorporates disphenoid, tetrahedral disphenoid honeycomb, and convex uniform honeycomb configurations. The roof structure employs a tetrahedral disphenoid honeycomb arrangement, while the walls feature two distinct geometric forms to demonstrate the versatility of SISA in applying uniform forms throughout the design. The rounded corners of the structure enhance the continuity of surfaces, facilitating a seamless transition into a horizontal polygonal configuration. The interplay between the façade elements and the roof and wall structures effectively demonstrates the purpose of the articulated frame geometrical panels, both structurally and architecturally. The integration of edge styling and the arrangement of open and closed panels within a rigid system create a cohesive and functional combination.



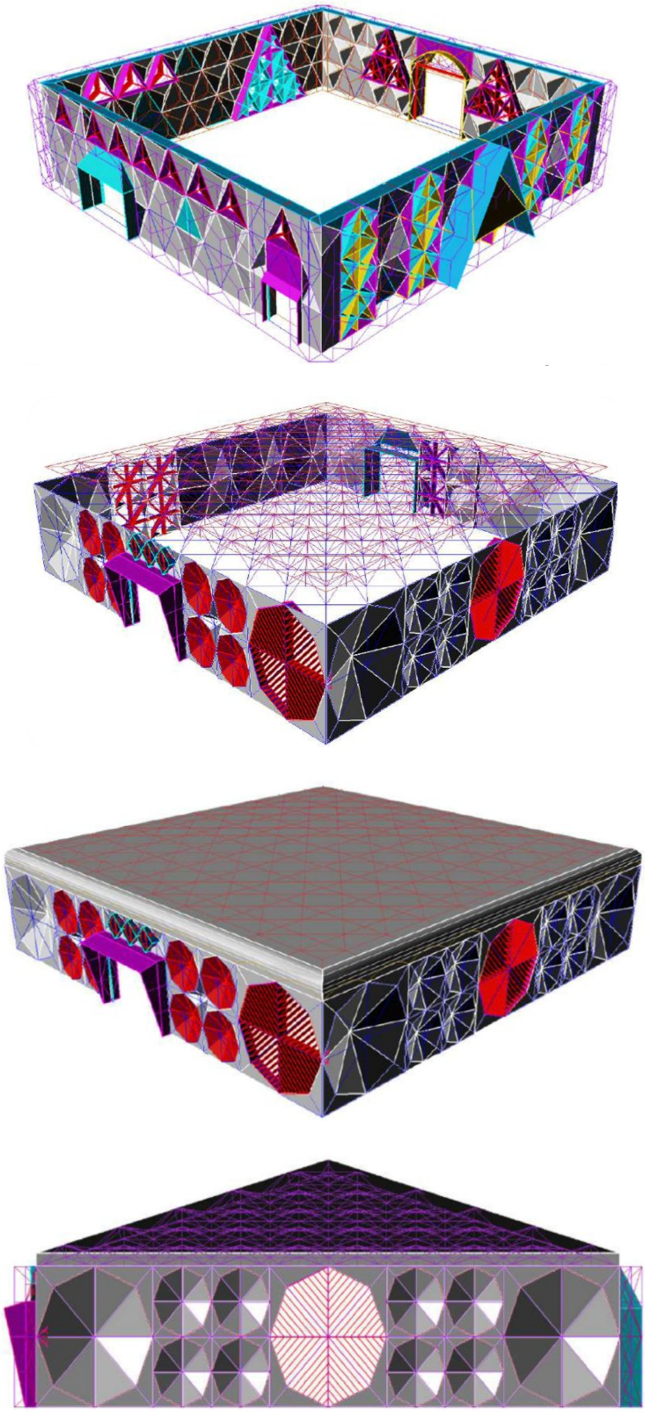


Figure 18. Conceptual design of a SISA-optimised structure using geometric configurations with sectional views.

6.1. Results and Discussion of the Presented SISA Design

The objective of this design was to investigate how SISA facilitates modifications in spatial design through effective surface articulation. SISA is proposed as a versatile system, allowing various combinations and permutations for conventional metal building facades. Without the inclusion of steel, smart glass, and plastics, implementing SISA would be unfeasible. The integration of space frame and folded plate systems in this design demonstrates a harmonious construction approach. Space frame components are intentionally buckled and shaped to form independent edges. This innovative approach signifies a shift in high-rise architecture, positioning SISA as a valuable building system with multifaceted functions in modern manufacturing.

The design is articulated through its exterior faces and frames, with edges providing a connection between new architectural configurations and composite designs. The SISA network is structured as a gradient system of layered sections, ensuring efficient structural performance and cost-effective construction. It connects both exterior and interior systems, featuring form lanes with a distinct identity for structural foam. The design addresses seasonal protection and shapes connections with regulated transitions. Key advantages include the creation of stable, sustainable configuration modules that enhance structural efficiency. The tessellated development utilises compression loads effectively, improving metal durability and providing protection against extreme climate and seismic forces. The architectural design highlights the integration of ecological and sustainable engineering principles, offering potential for future designs and improved housing quality.

The study results highlight the performance of the structural panels, including disphenoid, tetrahedral disphenoid honeycomb, convex uniform honeycomb, and tetrahedron configurations. Practical and theoretical design concerns emerged, particularly regarding cost implications and construction timelines. Engineers and architects need to address these concerns by consulting with geology and meteorology experts. Heavy loads, such as those from tornadic shear, may significantly impact the structural components. Effective construction involves careful application of materials and consideration of sustainability.

7. CONCLUSION

SISA is envisioned as a "Generic Building System and Technology," designed to create pioneering building components through a combination system using standard elements. SISA embodies the application of multiple configurations, permutations, and combinations in traditional metal building facades. It is advancing technological capabilities in various construction fields due to a new paradigm in building science. SISA offers surface articulation units for architects and engineers, promoting sustainability by adhering to circular principles of nature and optimizing the use of composite materials.

Research aimed at enhancing resource efficiency across industrial processes has highlighted the potential of SISA and material reuse. The system employs a systematic approach for integrating surface articulation, focusing on maximizing efficiency and profitability with unique stress on component use. Despite the extensive use of steel, smart glass, and other materials, the components of SISA work synergistically, allowing single-unit properties to handle distinct static and dynamic loads.

SISA has significantly contributed to the evolution of human-built environments. Various composites manufactured through multiple technologies have found broad applications. The SISA concept is applied in "new paradigm" research exploring high-rise construction without heavy concrete or steel and utilizing "Fractal Space Frame" structural systems alongside high-density, plant-derived foams and foamed glass fire protection.

SISA presents exceptional structural advantages, with its benefits increasing through experience. It offers immense satisfaction in various applications such as housing, factories, and bridges, especially under heavy and seismic loads. The lightweight and rigidity of the system contribute to its durability and resilience against seismic forces, making it ideal for seismic-prone areas. SISA's designs improve fire safety and sustainability, enhancing structural performance and offering a promising configuration for areas vulnerable to seismic and fire events.

The focus of SISA on using specific shapes is driven by efficiency and strength rather than strict form. The system's lightweight and strength offer significant advantages, but the design process is complex and time-consuming. Technological advancements have improved the ability to create efficient systems, and designers must prioritize efficiency, constructability, and durability in their designs.

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