

The Secondary Structure and Its Impact on the Architectural Formation of Building Envelope

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ABSTRACT

The advances in computer technologies have caused new architectural formations in contemporary buildings. They were characterized by free forms with diverse formal relationships that appear at different levels within the building, especially the surface formation level and the mass formation level. Also, the methods of embodiment of these formations and their mechanisms varied. Difficulties in distinguishing these new formations within the main structure have led to the need to find new structural solutions that embody these formations. In contemporary architecture, the relationship between the main and the secondary structure is defined by a hierarchy of the load-bearing roles. The research problem arises from the absence of clarification of the secondary structural role in embodying these formations. The research assumes that the secondary structural systems play an active role in embodying the architectural formations of the building envelope. Therefore, this study aims to uncover the potentialities of the secondary structures in the process of embodying the architectural formations, according to mechanisms of form generation. The research relies on the analytical approach to extract the indicators of the theoretical framework and then adopts the comparative analytical approach for five selected case studies of contemporary buildings and shows a variety in their use of secondary structure. The study finds that the secondary structure acts as a flexible structural medium, allowing it to produce complex forms according to the diversity in the mechanisms, depending on the methods of architectural formation. Therefore, the surface and mass formations transform from a static to a dynamic state.

Keywords: Building envelope, Mass formation, Secondary structural systems, Surface formation.

1. INTRODUCTION

The secondary structure is a crucial tool used in form expression, as it has transcended its limits as a structural function in contemporary architecture. The secondary structure is the

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structure that carries the loads of the façade and transfers them to the primary structure (**Knaack et al., 2014**). Architects have gained a greater role in controlling the architectural form of the building by dividing the building envelope. That is done by separating the secondary structure from its primary structure, thus enabling the creation of complex geometric forms. The secondary structure provides geometric flexibility to create free-form shapes by offering a flexible grid that adapts to the rigid primary structure (**Latif and Shahin, 2023**). Previous studies have addressed secondary structure in contemporary architecture from various perspectives. The study of (**Ismail et al., 2020**) deals with new techniques in designing complex and changing architectural forms. It focuses on the most important techniques that rely on fragmentation in architectural design. The study explains how to apply these techniques in relation to the concept of form, in order to give new, transformative features to architectural forms. The study indirectly referred to secondary structure through the fragmentation method (**Ismail et al., 2020**). The study of (**Shareef, 2021**) demonstrated the role of secondary structures in forming the facades of contemporary architecture. His study represented an analytical method and created a database of architectural proposals that dealt with surfaces according to structural relationships with multiple linking and modification mechanisms. The study applied all this to selected models of prominent architectural works throughout architectural history. Finally, the study reached the characteristics of formal compositions at the level of balance and stability that are results of the nature of these architectural surfaces and the relationships on which they are based (**Shareef 2021**). The study of (**Aldiwani and Shahin, 2023**) highlighted the role of secondary structural components in creating diversity and uniqueness in contemporary building facades (**Aldiwani and Shahin, 2023**). Meanwhile, (**Abdulhussain et al., 2023**) have revealed the most prominent mechanisms employed in architectural formation and addressed their role in creating form. The study indirectly referred to secondary structure through the rhythm method in architecture (**Abdulhussain et al., 2023**). On the other hand, (**Latif and Shahin, 2023**) emphasized the role of secondary structures in achieving structural flexibility by identifying the most prominent strategies and mechanisms that help achieve this flexibility (**Latif and Shahin, 2023**). The study of (**Yildiz and Yildiz, 2025**) examines the impact of the structural building through its external envelope to achieve sustainable design. The building envelope plays a pivotal role through the flexibility of its elements, which play an active role in sustainable design processes. The results show that the secondary structure of the building is a strategic element in achieving sustainability goals (**Yildiz and Yildiz, 2025**).

Previous studies can be divided into two categories: those that emphasized the secondary structure in terms of its importance in achieving the concepts of sustainability, structural flexibility, and achieving uniqueness and diversity for the components of the outer envelope, while neglecting its role in the architectural formation of the building. The second category focuses on the architectural form of contemporary buildings, particularly free forms, in terms of methods, mechanisms, and how they are generated according to engineering concepts. However, it did not address how they are embodied according to secondary structural systems and their types. These studies failed to establish a comprehensive understanding of their influence on architectural formation or to explain how they contribute to the generation and realization of contemporary architectural forms. Therefore, the current research fills a research gap by focusing on the relationship between the secondary structural systems and their role in embodying the architectural formation of the building envelope, as shown in **Fig. 1**. It assumes that the secondary structural systems play

an active role in embodying the architectural formations of the building envelope. The research aims to uncover the potential of secondary structure in the process of embodying the architectural formation, according to mechanisms of form generation.

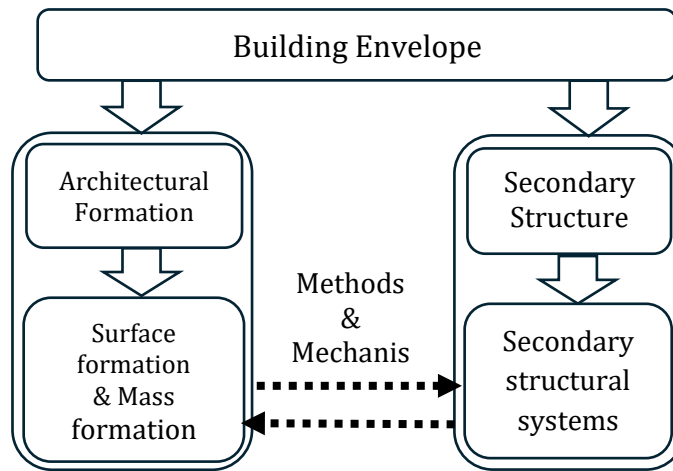


Figure 1. The concept of the research.

2. METHOD

The research relies on the analytical approach to extract the indicators of the theoretical framework and then adopts the comparative analytical approach for selected case studies according to specific criteria that serve the research objective, as shown in Fig. 2, and then discusses the results and comes up with a set of conclusions. The research will address, within its theoretical framework, two main aspects: the first deals with the secondary structure and its systems. The second deals with the architectural formation and the methods of generating them (Rhythm, Fracturing, Erosion, Porosity, Triangulation, Deconstruction and Reconstruction). The practical aspect focuses on applying the theoretical framework’s indicators to five selected case studies - cultural and commercial buildings - which are contemporary buildings between 2012-2023 and show variety in their use of secondary structure. and then adopts the comparative analytical approach for selected case studies.

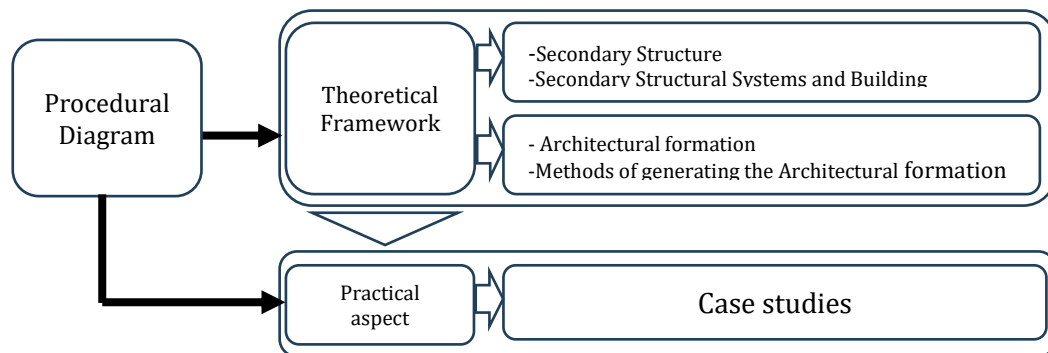


Figure 2. Procedural Diagram of Research



3. SECONDARY STRUCTURE

The function of the primary structure is to bear the load of the entire building and transfer it from the facade to the foundation. The secondary structure is the structure that carries the loads of the facade and transfers them to the primary structure (**Knaack et al., 2014**). In contemporary architecture, the relationship between the primary structure and the secondary structure is defined by a hierarchy of the load-bearing roles and the specialized functions. The primary structure (columns, beams, and shear walls) maintains the overall stability of the building and transfers loads to the foundation, while the secondary structure (purlins, girts, and facade frames) supports the cladding, glazing, and the interior elements, transferring these secondary loads to the primary structure (**Latif and Shahin, 2023**). In architectural design, hierarchy is not just an aesthetic decision, but a structural and cognitive necessity. As buildings become more complex and user requirements diversify, hierarchy becomes an essential tool for the architect to achieve clarity, ease of understanding (**Lakes, 1993**). So, secondary structures enhance both the functionality and visual appeal for the building, making them crucial.

4. SECONDARY STRUCTURAL SYSTEMS AND BUILDING ENVELOPE

Secondary structural systems, which rely on the primary structure for support, act as an “intermediary” between the main structure and the external envelope of interior space. Their function is not to structurally support the building, but rather to form the space and distribute load (such as wind pressure on the facade) to the main structure. They represent the bridge connecting the main structural system to the architectural envelope. The secondary structural systems play a clear role in the overall form of the building and are an integral part of its aesthetic expression and environmental performance (**Yildiz and Yildiz, 2025**). To highlight the role of the secondary structures in the overall form and aesthetic expression, the research classifies them according to their location within the building envelope into three main systems: Secondary facade structures, Secondary roof structures, and Integrated building envelopes.

4.1 Secondary Façade Structures

These structures are located on the vertical axis of the building. Its primary role is to provide a stabilizing network for the building envelope and to resist lateral wind loads, which includes two main types (**Ilgin et al., 2023**):

- Mullion and transom systems: These systems are the most common secondary structures for curtain walls, forming a grid to support glass or metal panels.
- Secondary steel sub-frames: Used in ventilated facades to support stone, ceramic, or composite cladding located away from the main wall to allow insulation and airflow.

Therefore, the effect of Secondary facade structures appears clearly at the surface formation.

4.2 Secondary Roof Structures

These structures are located on the horizontal or inclined axis at the top of the building. They bridge the gap between the trusses of the main large-span beams and the final roofing material. This includes three main types (**Miraglia et al., 2011**):

- Purlins: Longitudinal elements that rest on the main beams/trusses.
- Secondary beams: In light-gauge timber or steel construction, secondary beams provide direct support to the roof surface.



– Bracing beams: Used to stabilize the main roof trusses and prevent them from buckling. In contemporary architecture, the roof has transcended its traditional role as merely a horizontal covering, becoming a dynamic, free-form sculptural element that breaks away from the conventional horizontal plane (**Abramczyk and Prokopska, 2019**). This shift is due to several key factors, which are structural innovation and modern materials, as well as the emergence of parametric design and advanced computational tools that gave architects the possibility of designing complex curves (**Goldsmith, 2014**). So, the effect of secondary roof structures appears in the spatial formation as well as the mass formation of the building.

4.3 Integrated Building Envelope

In many contemporary “iconic” buildings, the secondary structure is not limited to walls or roofs, but acts as a unified envelope covering the entire volume of the building, including two main types (**Latif and Shahin, 2023**):

- Secondary diagonal grid frames: While some diagonal grids are primary (load-bearing), many contemporary buildings use a secondary diagonal grid or a “cage” space frame to support complex and non-straight geometric shapes.
- Double-skin facades: A secondary structure that creates an “envelope within an envelope” is used as thermal insulation and integrated shading.

Thus, the effect of the integrated building envelope significantly emphasizes the mass formation of the building.

5. ARCHITECTURAL FORMATION

According to the previous classification of Secondary structural systems, there are three levels of architectural formation that can be identified :Surface formation, Spatial formation, and Mass formation.

- Surface formation: The secondary structure acts as a “skin structure”, translating the abstract architectural surface into a physical reality by the treatment of the skin that gives the building its final form (**Shareef, 2021**)
- Spatial formation: The secondary roof structure often defines the upper boundary of the interior space. It provides protection, establishes a “fifth façade”, and creates a visual rhythm that lends a distinctive character to the interior (**Ilgin et al., 2023**).
- Mass formation: Integrated building envelopes (often referred to as exterior structures or unified envelopes), represent an ideal convergence between the secondary structure and the overall form of the building. Unlike a simple façade, an integrated envelope encloses the entire building, often blurring the dividing line between the wall and the roof to define the building’s mass formation, therefore defining the overall geometry (mass expression) (**Cullufi et al., 2014**).

The study finds that in the mass formation level, the integrated envelope either works in harmony with the main structure (aligning with the building’s external boundaries) or creates a new independent volume outside the boundaries of the main structural framework. The components of the secondary structural framework are controlled by methods that define the relationship between the elements in order to generate the form. The study will focus on both Surface formation and Mass formation, as they influence the architectural formation of the building envelope, which is the subject of this study.



6. METHODS OF GENERATING THE ARCHITECTURAL FORMATION

In contemporary architecture, Architectural formation methods are generative tools for form-finding. This study will address the most common methods that affect the formation of the building envelope.

6.1 Rhythm

Rhythm in nature is a dynamic balance. It creates a structural “pulse” that is constant in its logic but oscillates in its form, resulting in a harmonious and unique visual experience **(Alshami et al., 2015)**. According to “Spiral Theory”, rhythm reflects ways that align with the requirements of growth and development. This is known as the Law’s nature, “Law of leaf arrangement **(Greenbaum and Kyng, 2020)**. Therefore, rhythm is considered a human response to desires because it consistently reflects biological characteristics. Repetition is one of the basic “laws of unity” in the arts and architecture, along with centrality, proportion, balance, and others, which contribute to creating rhythm **(Abdulhussain et al., 2023)**. In the context of architecture, unity allows highlighting structural logic and contributes to creating a sense of order. For example, the use of proportional symmetry, axial alignment, and standard repetition in architecture exemplifies how unity leads to a visual organization and a distinctive spatial experience **(Chen et al., 2025)**. It consists of a constant or variable set of “joints -elements” linked in harmony to maintain the visual forces’ equilibrium **(Abdulhussain et al., 2023)**. Architects achieve the concept of rhythm using “parametric modification” algorithms, allowing designers to create a façade where the primary (constant) unit remains unchanged, while its rotation or size (variable) on its surface shifts according to patterns of sunlight or wind **(Alshami et al., 2015)**.

6.2 Fracturing

Fractals are self-similar groups whose patterns are made up of miniature copies of themselves, giving them the property of self-similarity across different scales. Using fractal shapes is considered one of the most effective techniques in architectural composition, as they give the architectural form special characteristics such as dynamic, unity, and diversity **(Ismail et al., 2020)**. A fractal, whether it is a geometric shape or a natural object, shares a set of characteristics. Its parts have the same shape or structure as a whole but differ in scale and may also be slightly distorted. The shape of the unit is irregular or fragmented, and it remains so regardless of the scale of the examination. Its irregular form of structural unit makes it difficult to describe using traditional Euclidean geometry **(Belma and Sonay, 2016)**. Fracturing in secondary structures is defined as a system of ordered complexity where a simple generative rule is repeated to create multiple scales configuration. Using fractional logic, the structure achieves a rhythm that is both constant and variable. It is constant through the repetition of its basic algorithmic rules, and variable through the wide range of scales and fractional ratios that break the monotony of the building envelope **(Osama et al., 2014)**.

6.3 Erosion and Porosity

Erosion in nature can be considered a continuous process of transformation at both the macro and micro levels, where patterns are formed through the deposition or removal of materials. Similar to that are the forms resulting from porosity formed, as in the case of rocks



altered by natural forces such as wind and rain (**Wendland, 2000**). Currently, many architects draw inspiration from these changing natural processes to create complex, free-form structures and unprecedented transitional characteristics. Advancements in digital architecture offer limitless tools and techniques in design and conceptualization. Therefore, there are numerous types of erosion that have inspired architecture through various techniques. This concept is applied in architectural form by changing the form of horizontal or vertical planes to achieve curvatures to the form, and stripping them out, or by creating a transformation through applying wide porosity to the form (**Ismail et al., 2020**). The porous structure has positive effects on the building envelope, which enhances communication between the inside and outside and creates new relationships between building elements (**Kotsopoulos, 2008**).

6.4 Triangulation


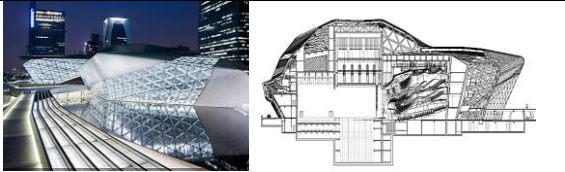

Triangular structures are based on simple and powerful geometric principles that utilize triangular shape. The triangle is the only polygon that is rigid in nature, unlike squares or rectangles, a triangle fixes its angles by fixing the lengths of its sides (**Welch and Witkin, 1994**). In such a structure, there is a requirement that each side of the triangle is shared completely between two adjacent triangles. So, a surface that contains a countless number of triangulations is a grid of triangles, named by specialists as a compact surface. Here, the Eiffel Tower is a well-known example of it (**Ismail et al., 2020**). Triangulation systems are typically used for their inherent structural properties; the prismatic patterns which they produce also lend considerable visual appeal to the construction of three-dimensional form. So, triangulation is a technique for creating a stable structure using interconnected triangles. The triangular secondary structure resists deformation because changing its shape requires changing the length of its members, which requires a lot of energy. This geometric rigidity allows designers to control deflection, vibration and overall stability without increasing mass (**Hameed et al., 2020**).

6.5 Deconstruction and Reconstruction

The Process of deconstruction and reconstruction is one of the mechanisms that expresses the idea of “Constant and changing rhythm”. It begins by breaking down the mass into its basic elements, then reassembling it in a new way to create visual diversity. The process of creating an architectural form involves three stages: First, the stage of mass deconstruction, then the rearrangement of the layers of the deconstructed parts using either horizontal, vertical, or diagonal connections. After that, the transformation process begins by using the chosen element, rotating and shifting it, and changing its scale (**Ismael et al., 2025**). Many architects have used this technique, known as “assemblage”, which has given their buildings a design language characterized by angles and slanted volumes, thus creating visual tension and mystery. This technique relies on structuralism as the starting point in forming and deconstructing forms, so that it is impossible to understand the architectural work as an integrated unit, but rather as a single unit within its context. Here, each part of the architectural composition has a different function and characteristics that allow it to be formed within an integrated system, and not individually (**Nilsson, 2013**).

From the previous discussion, the research reaches a set of indicators that can be derived from the methods of generating the Architectural formation, including the mechanisms of visual organization and its expressive values, as shown in **Table 1**.

Table 1. The indicators of the methods of generating the Architectural formation.

Methods of generating the Architectural formation.	Project	Mechanisms of Visual Organization
Rhythm	 <p>John Curtin School of Medical Research at the Australian National University, 2006 (Lyons, 2026).</p>	<ul style="list-style-type: none"> -Proportional symmetry -Axial alignment -Standard repetition (Unity)
Fracturing	 <p>Centenary of the federation of Australian States (Osama et al., 2014; Belma and Sonay, 2016).</p>	<ul style="list-style-type: none"> - Self-Similarity - Multiple scales - Generative Repetition
Erosion – Porosity	 <p>King Abdullah Financial District Metro Station designed by Zaha Hadid (Selim et al., 2024). Palazzo Itadio, Milano Italy (Zid, 2025).</p>	<ul style="list-style-type: none"> -Changing the form of horizontal or vertical planes to achieve curvatures to the form. - Create porosity to the form.
Triangulation	 <p>Guangzhou Opera House, designed by Zaha Hadid. (Hadid, 2026).</p>	<ul style="list-style-type: none"> - Create complex forms. - Clear geometrical shape of each unit. - Resemblance between the whole and the parts.
Deconstruction and Reconstruction	 <p>Guggenheim Museum Bilbao, designed by Frank Gehry (FMGB, 2026).</p>	<ul style="list-style-type: none"> -mass deconstruction, rearrangement of the layers, and a transformation process.

7. PRACTICAL ASPECT: CASE STUDIES

The research selected five case studies to test the research hypothesis and achieve its objective. The selected cases are characterized by the following:

- All cases are cultural and commercial buildings, where architectural formation plays a significant role in their design.
- All cases are contemporary buildings constructed between 2012-2023.



- The cases show variety in their use of secondary structure and their impact on the architectural formation.

The research identified a set of primary and secondary indicators derived from the theoretical framework. These will be tested in the practical aspect of the study to verify the hypothesis and achieve the study's objectives, as shown in **Table 2**.

Table 2. The primary and secondary indicators from the theoretical framework

levels of architectural formation	Main Indicators Systems of Secondary Structure	Secondary Indicators, Methods of generating Architectural formation and Mechanisms of Visual Organization	Vocabulary of Architecture Formation by Secondary Structure
- Surface formation - Mass formation	-Secondary façade Structures -Secondary roof Structures -Integrated building envelopes	Rhythm: – Proportional symmetry – Axial alignment – Standard repetition (Unity)	- Structural logic. - Sense of order.
		Fracturing: – Self-similarity – Multiple scales – Generative repetition	- Irregular form of a structural unit. - Complexity order.
		Erosion – Porosity: – Changing the form of horizontal or vertical planes to achieve curvatures in the form. – Create porosity in the form.	- Irregular form of a structural unit.
		Triangulation: – Create complex forms. – Clear geometrical shape of each unit. – Resemblance between the whole and the parts.	- Flexibility of Secondary Structure. - Construction of a three-dimensional form.
		Deconstruction and Reconstruction: – mass deconstruction, rearrangement of the layers, and a transformation process.	- Diversity in secondary structure components.

7.1 Wisma Atria (Façade Regeneration and Retrofitting)/ Singapore-2012

- Design: DP Architect
- General Description of the project: The shopping center has undergone continuous renovation and modernization to reflect the spirit of age. The building's design company has transformed it over nearly three decades, from its distinctive blue façade to its crystalline one.
- Conceptual design and Architectural Formation: The design of the new articulated façade is inspired by a precious jewel, emerging from a rough rock, creating a new and distinctive image for the mall, while simultaneously enhancing and enriching the Orchard Street experience and boosting the visual impact.

The secondary steel structure wraps around the existing building. A secondary steel mesh was installed on the original reinforced concrete structure. High-strength steel supports were installed in the existing floor slabs to highlight the new façade. The secondary structure



is complemented by a matte aluminum finish for the structural cladding systems, aluminum composite panels and double-glazing units (DP Architects, 2012), as shown in Table 3.

7.2 The Crystal (A pavilion in a park)/ London-2012

- Design: Wilkinson Eyre Architects
- General Description of the project: As an exhibition Centre and think tank, it has received outstanding BREEAM and LEED Platinum ratings, because of its environmental and technological strategies
- Conceptual Design and Architectural Formation: The building's design was inspired by nature, specifically its crystalline geometry with its parallelogram shape that includes several triangular faces. However, in addition to the aesthetic effect, the building's angles, whether on its roof or facades, are strategies to reduce direct exposure and limit its temperature rise. Unlike a traditional roof placed over walls, the roof and walls of the crystal building are part of a connected secondary steel system inspired by origami that warps around the primary concrete and steel core. 1580 m² of photovoltaic solar panels were installed, covering two-thirds of the roof, and these panels generate 20% of the building's energy. The secondary structure of London's Crystal building is an example of a structural envelope, where the secondary framework is inseparable from the building's distinctive aesthetic (Shinoda and Meirelles, 2024; Yildiz and Yildiz, 2025), as shown in Table 3.

7.3 The Broad Contemporary Museum/Los Angeles, USA- 2015

- Design: Diller Scofidio and Renfro
- General Description of the project: The Museum of Contemporary Art serves as the home of the Broad Art Foundation's international lending library. It is LEED Gold certified. The three-story building houses galleries, storage facilities, and service areas.
- Conceptual design and Architectural Formation: The Building's Architectural Formation is based on a unique duality known as the "veil and vault", the vault represents the primary structure (The solid mass); it is the heart of the concrete building that combines the storage space and facilities, whereas the Veil is the Secondary Structure that completely envelops the building. It is a complex system. The Secondary Structure is a porous, honeycomb-like exterior structure that extends the length of the building's mass, providing filtered natural light. Composed of asymmetrical elements, this porous outer shell, made up of 2500 glass fibre reinforced concrete (GFRC) panels, achieves both aesthetic and functional effects, supported by a secondary steel frame (Baldwin, 2026), as shown in Table 3.

7.3 Changsha Meixihu International Culture and Art Centre/ China-2019

- Design: Zaha Hadid Architects
- General Description of the project: The new Culture and Arts Centre comprises three separate cultural institutions, including a museum of contemporary art, an 1800-seat theatre with supporting facilities, and a multi-purpose hall. The centre features an organic architectural design and overlooks the adjacent lake, Meixi.
- Conceptual design and Architectural Formation: The design uses the principle of dynamic fluidity to create a sense of continuous movement, avoiding sharp corners or traditional box-like barriers.


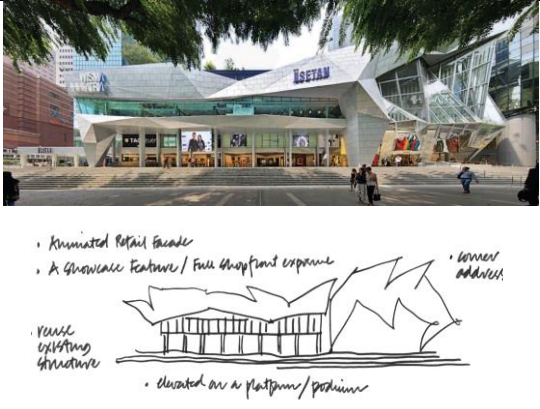
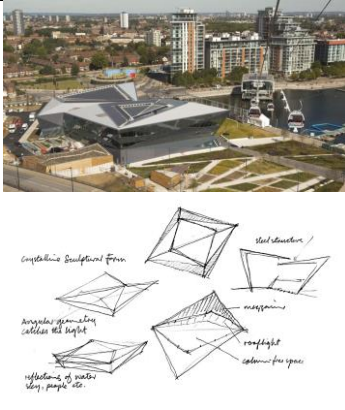
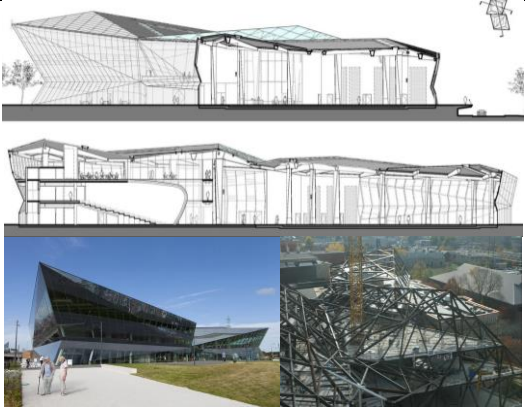
The outer shell features a white wavy covering that extends across the buildings and plaza. Flow and interconnection are a simulation of river flow. The envelope provides shaded

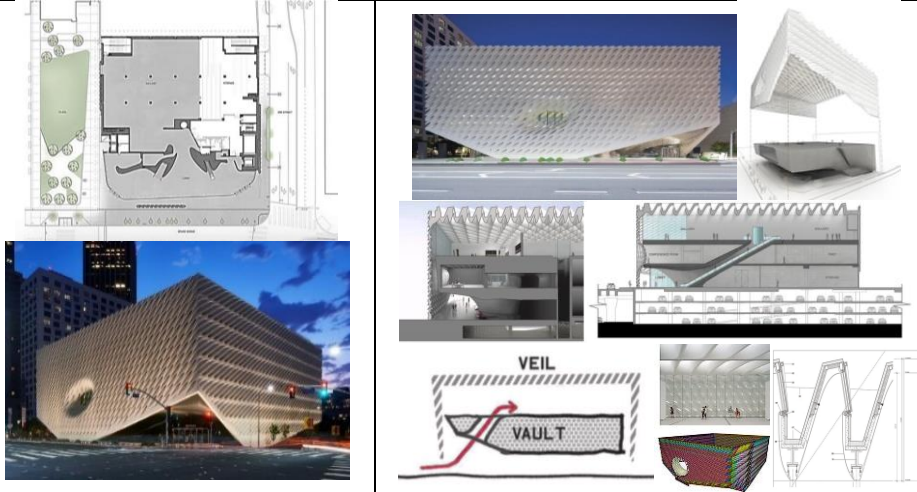
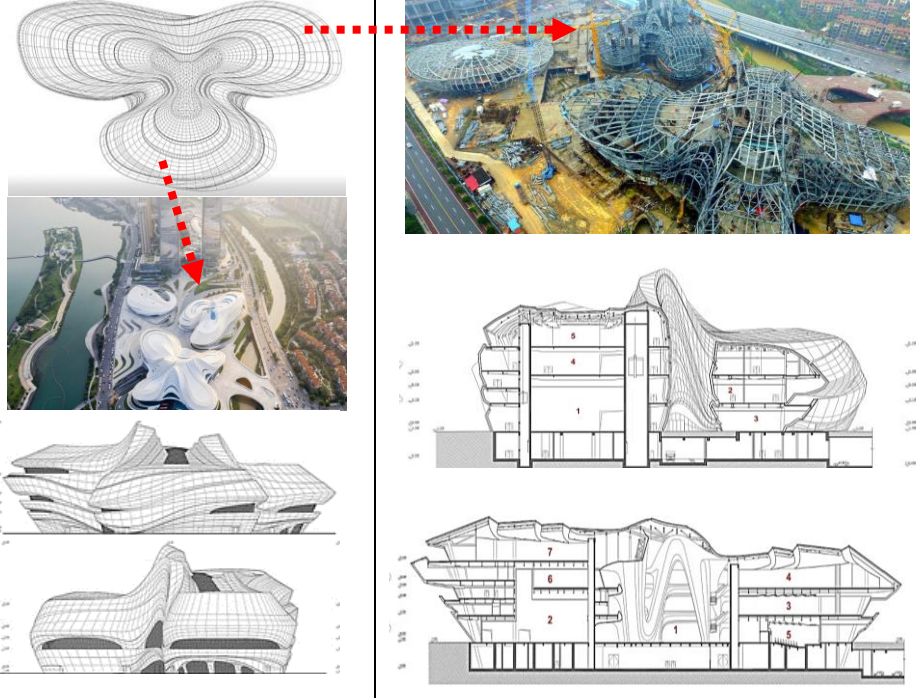
walkways and exciting entry points, guiding visitors through “valleys” of architectural formations. Structural systems are designed using the curtain wall system design algorithm. This concept of using prefabricated materials in post-parametric automation can be observed in the design and construction of complex buildings (Mangaroska, 2021), as shown in Table 3.

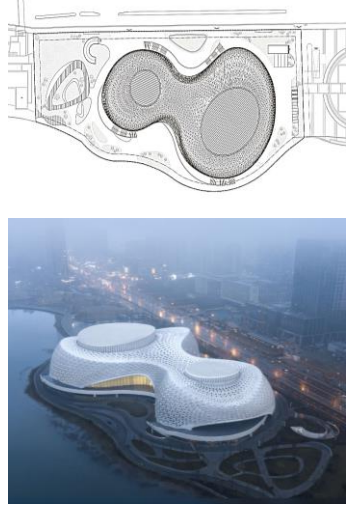
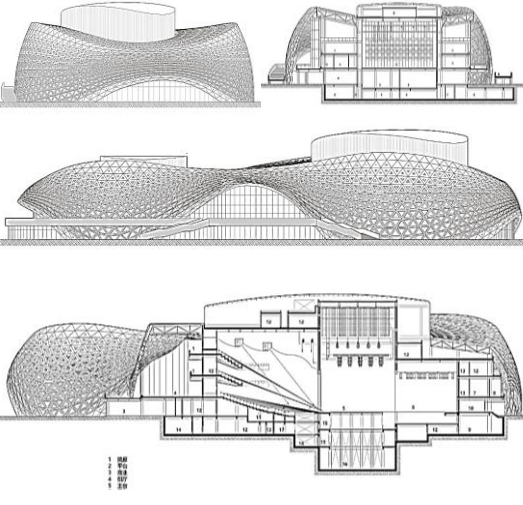
7.4 The Golden Sands Lake Grand Theatre/ Hangzhou, China-2023

- Design: CCTN Design
- General Description of the project: The building is situated on the banks of a lake and houses a variety of functions, including a 1400-seat theatre and a 500-seat multi-purpose hall, along with multi-purpose facilities and training rooms.
- Conceptual design and Architectural Formation: The theatre’s form is characterized by its flexibility and undulation, allowing it to blend seamlessly into the urban environment. The building’s perforated surface creates an open space that acts as a link between its exterior and interior functions. The secondary structure consists of 5000 triangular elements of different sizes to form the building’s shell and create a harmonious blend of solidity and void. The design of the theatre is a prime example of parametric design and organic architecture. The building’s design was inspired by the movement of water and moving dunes (Wang, 2026), as shown in Table 3.

Table 3. Case Studies.

No.	Project	Figures of Architectural Formation	Figures of Secondary Structure
1	Wisma Atria (Façade Regeneration and Retrofitting)/ Singapore-2012		 <p> • Minimal Retail facade • A Showcase feature/ Full shopfront exposure • corner address • reuse existing structure • elevated on a platform/podium </p>
2	The Crystal (A pavilion in a park)/ London-2012	<p>(DP Architects, 2026)</p>  <p> crystalline sculptural form angular open-plan section all height reflections of water, sky, people etc. steel structure / massing rooflight column-free space </p>	

<p>3</p>	<p>The Broad Contemporary Museum/ los Angeles, USA- 2015</p>	<p>(Babu, 2026)</p>  <p>(Baldwin, 2026)</p>	
<p>No.</p>	<p>Project</p>	<p>Figures of Architectural Formation</p>	<p>Figures of Secondary Structure</p>
<p>4</p>	<p>Changsha Meixihu International Culture and Art Centre/ China- 2019</p>	<p>(Hadid, 2026)</p> 	

<p>5</p>	<p>The Golden Sands Lake Grand Theatre/ Hangzhou, China-2023</p>		
		<p>(Wang, 2026)</p>	

8. RESULTS AND DISCUSSION

According to the analytical study of the selected examples and based on the primary and secondary indicators derived from the theoretical framework, as shown in **Table 4**, the following results were found:

Table 4. The primary and secondary indicators for case studies

	Project	Levels of Architectural Formation	Main Indicators, Systems of Secondary Structure	Secondary Indicators, Methods of Formation Generation and Mechanisms of Visual Organization	Vocabulary of Architecture Formation by Secondary Structure
1	<p>Wisma Atria (Façade Regeneration and Retrofitting)/ Singapore-2012</p>	<p>Surface formation (Dynamic envelope at the Vertical axis of the building).</p>	<p>Secondary façade structures</p>	<p>Fracturing: -multiple scales of triangle surface.</p>	<p>Secondary steel sub-frames: The structure uses a series of irregular, complex forms of structural units (triangular and trapezoidal steel frames).</p>
2	<p>The Crystal (A pavilion in a park)/ London-2012</p>	<p>Mass Formation (The roof design, along with the main facades, defines the building's crystalline shape).</p>	<p>Secondary roof + facade structures</p>	<p>Fracturing: -multiple scales of triangle surface. -Self-Similarity uses the shape of triangles in more than one place.</p>	<p>Bracing beams at roof + Secondary steel sub-frames: irregular, complex steel diagrid and folded-plate system at façade.</p>



3	The Broad Contemporary Museum/ Los Angeles, USA- 2015	Mass formation, (Unified envelope, It offers a sculptural form that challenges the traditional “square geometric” form)	Integrated building envelope	<p>Rhythm: -modular unit that forms a continuous and homogeneous cover.</p> <p>Porosity: Creating porosity in the shape through repeated cavities.</p>	<p>Double-Skin Facades: The structure is a complex assembly of modular units that reflects the structural logic. An order of three-dimensional structural steel grid that acts as a semi-independent external structure. It is based on rhombic structural cells - irregular units - allowing for self-bending and efficient load distribution.</p>
4	Changsha Meixihu International Culture and Art Centre/ China- 2019	Mass formation, (Unified envelope that erases the dividing line between the ground and the building).	Integrated building envelope	<p>Erosion: - The parametric design was used in the envelope to change the form of horizontal or vertical planes to achieve a complex curve.</p>	<p>Secondary diagonal grid frames: The structure is a complex irregular secondary steel frame that connected the primary reinforced concrete structure with the outer GRC panels. -Based on triangulation and Non-Uniform Rational B- Splines NURBS curves, to create accurate, smooth, and adjustable curves and surfaces, ensuring their structural stability.</p>
5	The Golden Sands Lake Grand Theatre/ Hangzhou, China- 2023	Mass formation (unified envelope where the boundaries between vertical and horizontal elements fade away. A smooth transition between the roof and walls)	Integrated building envelope	<p>Erosion: The parametric design was used in the envelop to create curvatures to the form, inspired by the movement of water and sand dunes.</p> <p>Porosity: -Variable Density: the “pores” or opening change in size based on functional needs.</p>	<p>Secondary diagonal grid frames: The secondary structure consists of irregular structural unit to form the organic building’s shell. Between the main concrete structure and the outer layer is a system of adjustable steel supports. These technologies allow for millimeter-level accuracy when installing outer panels and create the pores for the curves.</p>



- The analytical study of the Wisma Atria (Façade Regeneration and Retrofitting) reveals that the secondary structural system, represented by the secondary steel sub-frames, acts as a flexible structural intermediary between the building's rigid structure and the added flexible skin, embodying the surface formation. This secondary structure system has an active role in achieving the conceptual design of rehabilitation without changing the primary structure of the building. A series of irregular, complex forms of structural units was adopted in accordance with the fracturing mechanisms that produce complex triangular surfaces. So, the building surface formation plays a clear role in transforming the building's façade from a two-dimensional configuration to a three-dimensional formation, making the building a visual icon.

- The analytical study of the Crystal (A pavilion in a park) reveals that the secondary structural system, represented by bracing beams and steel sub-frames at the roof and facades, acts as a flexible structure, embodying the mass formation. The secondary structure achieves the conceptual design of producing crystalline geometry with a parallelogram shape that includes several triangular faces. Irregular complex steel diagrid and folded-plate system at the façade was adopted in accordance with the fracturing mechanisms and the production of multiple scales of triangular surface at the roof and façade. So, the secondary structure participated in the creation of three multi-faceted surfaces in different directions that correspond to the movement of the sun and wind, in order to benefit environmentally from those surfaces.

- The analytical study of the Broad project reveals that the secondary structural system, represented by the double-skin facades, acts as a sculptural form that challenges the traditional square geometric form, embodying the mass formation and supporting the conceptual design of "veil and vault". A complex assembly of modular units that reflects the structural logic, and an irregular unit that reflects the fluidity in limited parts of the mass, were adopted in accordance with the rhythm and porosity mechanisms to produce an integrated building envelope. So, more than one method of formation generation and mechanisms of visual organization were adopted in its design: Rhythm was adopted as a basic architectural formation through the repetition of structural units, reflecting a porous expressiveness to the building envelope. A kind of fluidity was created in limited parts of the building envelope using the erosion mechanisms. In The Broad, the secondary structure is no longer merely an envelope for the building but has become a dominant architectural formation that defines the building's form, environmental function, and visual identity. This transformation is the essence of the architectural impact of secondary structural systems in contemporary digital architecture.

- The analytical study of the Changsha Meixihu International Culture and Art Centre reveals that the secondary structural system, represented by the diagonal grid frames, acts as an active part in the process of transformation. Here, the architectural formation turns from a static into a dynamic concept, enhancing the activation of the surrounding urban space and embodying the mass formation, and supporting the conceptual design that aims to create a dynamic mass. The tendency of this case study is related to erosion mechanisms. Herein, the complex irregular secondary steel frame which connects the primary reinforced concrete structure with the outer GRC panels has transformed, according to erosion, and produced accurate, smooth, and adjustable curves and surfaces. So, that demonstrates the possibility of achieving extreme organic fluidity through the repetition of irregular triangular secondary components and modular units. Nevertheless, the structural nodes follow a fixed mathematical logic to create an erosion form.



- The analytical study of the Golden Sands Lake Grand Theatre reveals that the secondary structural system, represented by the diagonal grid frames, acts as a flexible structural intermediary between the building's rigid structure and the flexible skin, embodying the mass formation. Here, the conceptual design of seamless blending into the urban environment has been achieved. A series of irregular structural units was adopted in accordance with the erosion and porosity mechanisms to form the organic building envelope and contribute to creating a visual connection between interior and exterior spaces. So, here the concept of porosity has been demonstrated, which is a vital architectural strategy used to break the solidity of the mass and create a match between the interior and exterior by forming cavities and porous structures. The space between the primary structure –concrete core- and the secondary structure –outer steel skin- acts as a 'porous zone'.

- The degree of independence of the secondary structure decreases with increasing building height, as it becomes more dependent on structural stability requirements and wind loads, thus imposing greater constraints on modular freedom compared to low- and mid-rise buildings.

Considering all the previous information acquired through the theoretical framework, the results of the practical study, the application of the primary and secondary indicators for the case studies, and the discussion of the results, the validity of the research hypothesis is confirmed, which states: The secondary structural systems play an active role in embodying the architectural formations of the building envelope. It was revealed that the secondary structures have high potential in the process of embodying the architectural formations, according to mechanisms of form generation.

9. CONCLUSIONS

- In contemporary architecture, the function of the secondary structure is no longer limited to being a supporting structure for the building envelope; rather, it has become the tool that liberates form from the constraints of gravity and the rigid structural logic of columns and beams. The primary structure provides logic, while the secondary structure provides the language, and the architectural formation is the resulting dialogue between them. The secondary structural systems give the designer the ability to produce free forms.
- Architectural formation is achieved through feedback between the visual organizational mechanisms for generating and the secondary structural systems of the building envelope.
- Secondary structural systems play an active role in the process of transforming surface and mass formation from a static to a dynamic concept by creating diversity in the mechanisms of architectural formation.
- The secondary structural systems enhance the activation of the surrounding urban space by forming a continuous surface from the floor to the wall and the roof with high fluidity.
- The secondary structural systems contribute to creating a visual connection between interior and exterior spaces by forming cavities and porous structures in the building envelope. Its permeability can be controlled with the help of parametric design.
- Secondary structural systems achieve the concept of flexibility through the possibilities of subtraction and addition to the building envelope, supporting its rehabilitation.
- The secondary structural systems act as a flexible structural medium that fills the gap between the rigid structure and the flexible skin, allowing the production of complex forms that the primary structure is unable to express.



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Credit Author Contribution Statement

Aseel Latif: Conceptualization, Methodology, Data collection, Formal analysis, Writing – original draft. Hala Aldiwani: Conceptualization, Methodology, Formal analysis, Writing - review & editing. Asmaa Al-Ani: Formal analysis, Writing -review & editing, Validation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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النظام المنشئي الثانوي وأثره في التشكيل المعماري لغلاف المبنى

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الخلاصة

أدت التطورات في تقنيات الحاسوب الى ظهور تشكيلات معمارية جديدة في الابنية المعاصرة. تميزت تلك التشكيلات بالأشكال الحرة ذات العلاقات الشكلية المتنوعة وعلى مستويات مختلفة ضمن المبنى، لاسيما مستوى التشكيل السطحي ومستوى التشكيل الكتلي، كما تنوعت أساليب وآليات تجسيد تلك التشكيلات المعمارية. وقد ظهرت صعوبات في تمييز هذه التشكيلات الجديدة ضمن النظام المنشئي الرئيسي، مما أفرز الحاجة الى إيجاد حلول منشئية جديدة تقوم بتجسيد هذه التشكيلات. في العمارة المعاصرة تتعرف العلاقة بين النظام المنشئي الرئيسي والثانوي عن طريق تسلسل الأدوار في حمل أثقال المبنى. برزت المشكلة البحثية في غياب توضيح دور المنشئي الثانوي في تجسيد تلك التشكيلات. يفترض البحث بأن النظم المنشئية الثانوية تؤدي دوراً فاعلاً في تجسيد هذه التشكيلات المعمارية لقشرة المبنى، ومن ثم تهدف هذه الدراسة الى الكشف عن إمكانيات النظم المنشئية الثانوية في عملية تجسيد التشكيلات المعمارية، وفقاً لآليات التوليد الشكلي. يعتمد البحث على المنهج التحليلي لغرض التوصل الى مؤشرات الإطار النظري، ثم ينتهج أسلوب التحليل المقارن لخمسة أمثلة مختارة للدراسة من الابنية المعاصرة، مع إظهار التنوع في استخدامها للنظم المنشئية الثانوية. استنتجت الدراسة بأن النظم المنشئية الثانوية تؤدي دور الوسيط المنشئي المرن الذي يسمح بإنتاج تشكيلات معقدة بسبب تنوع الآليات التي تعتمد على أساليب التشكيل المعماري. ومن ثم تحولت التشكيلات السطحية والكتلية من الحالة الساكنة الى الحالة الديناميكية

الكلمات المفتاحية: قشرة المبنى، التشكيل الكتلي، النظم المنشئية الثانوية، التشكيل السطحي.