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A Study on the Stabilization Methods of Structural Systems and the Form-active Characteristics of Buildings (Focusing on Early Modern Buildings)

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Abstract: Integrated designs involving structure and design are closely intertwined with the initial stages of architectural design. Although the integration of structural systems and architectural aesthetics is a core element of contemporary design, existing studies have often treated structural efficiency and spatial form as independent factors. In most cases, the focus has been on areas where structural systems play a primary role, such as the relationship between structure and building materials, the development of structural analysis software, and the design of high-rise buildings. Consequently, there is a lack of empirical analysis on how structural systems directly influence the composition of architectural space. To address this, the MIDAS program was used to visualize areas of concentrated bending moments and load flow, and analyze the interrelationship between structural stability and spatial form. The analysis results indicate that structural systems classified as Skeleton and Truss types perform distinct spatial roles. Structures that emphasize architectural forms (e.g., lattice trusses, geodesic domes, and tapered skeleton structures) are primarily used for roof construction. Conversely, structures defining the architectural space (rectangular skeleton structures and Vierendeel trusses) are primarily employed for horizontal floor slab construction through stress redistribution.

Keywords: Skeleton structure; Structural stability factors; Structural system; Truss structures

1 INTRODUCTION

1.1 Background and Purpose of the Study

A building forms a space through the physical combination of floor slabs and walls, and its form consists of a roof that responds to stress. Buildings pursue different stabilization methods based on the structural system that responds to stress, and each has its own unique formal characteristics. Therefore, a building is characterized by its floor plan, which defines the space and form of the roof with its characteristic envelope.

Vitruvius, in his book De Architectura around 25 BC, defined the essence of architecture as commoditas, firmitas, and venustas. This is explained by Italian architect and engineer Pier Luigi Nervi in his book New Structures (1963), in which he describes function, structure, and form as essential elements of a building, stating that architecture is completed when these three elements are harmoniously combined. The structure, as the most fundamental element of a building, is the structural system. The structural system that influences the architectural form usually has a naturally curved shape that follows the flow of loads.

Historians are interested in buildings as a way of evaluating an era because architecture is the result of the complex interaction of history, culture, and scientific technology of that time. Knowledge of structural behavior and mechanical properties is necessary to understand buildings and set design criteria. The structural system has an absolute influence on determining the physical size of the floor plan and constituting the external form. Modern architecture can be considered a case in which the new materials of that era—plate glass, reinforced concrete, and steel—and the technology of the structural system were actively reflected in the form of buildings.

Examples of prior research are as follows.

Sev and Tugrul [1] classified the structural systems used in high-rise building designs and specifically investigated structural analysis and digital design methods for high-rise buildings with nonstandard forms. They also emphasized the importance of integrating architectural and structural designs.

Uihlein [2] conducted interviews with practitioners to examine structural integration. The interviews were organized into areas such as the collaborative relationship with structural engineers during the design phase, the role of the structure, the criteria for evaluating architectural design, and the characteristics of structural integration. In other words, expert interviews were used as the research methodology.

Li et al. [3] regarded structure as the primary agent of morphogenesis by conducting experiments on tension, compression, curved surfaces, and load deformation. They observed that structural rationality profoundly influenced spatial composition, whereas the performance of construction materials also served as a key factor in generating form. Through these four experiments, they advocated the integration of structure and design.

Jin-ho et al. [4] proposed an integrated structural design system and a model for buildings. Based on structural analysis, they developed a design model by modeling the main structure, substructure, and connection structure. In other words, this research focused on developing a model in which the structural analysis results took precedence over the integration of the architectural design and structure.

Janakieska [5] defined structural systems as factors influencing building design, setting parameters such as room size, circulation paths, furniture, and functionality, and conducted a case study limited to hotel architecture.

Ahmed El-Khadrawy [6] examined the influence and correlation between geometric patterns found in nature (triangles, hexagons, and lattice structures) and the structural systems and spatial configurations of modern architecture. He analyzed buildings with truss structures and focused his research on the geometric composition of exterior forms rather than on interior spaces.

Kookalani et al. [7] focused on developing programs to enhance productivity and achieve optimized designs through automation of architectural and structural designs. The

authors presented methods for automating the structural design using generative design (GD), deep generative models (DGM), and topology optimization (TO). They also proposed a hybrid approach that integrates these design methods according to the project characteristics. However, the program primarily focuses on structural systems, with insufficient coverage of integrated designs and spatial considerations.

Firdevs Kozan [8] used structural analysis software (SAP2000) to model various exterior structural forms, including tubular frames, tubular diagrids, and lattice diagrids, and conducted a quantitative study of seismic loads and load behavior. The study focused on high-rise buildings, where the use of structural systems is essential. This research also primarily focuses on external structural forms, and it can be considered to lack sufficient discussion of interior floor plans.

Acican and Luyten [9] conducted a project involving architecture students, in which each student's project progressed through structural systems and structural analysis within the architectural design curriculum. The structural simulation results were applied to architectural project design. Students received feedback from experts to develop their designs and approached the integration process of architectural structure and design within an educational context.

Mario Rinke and Robbe Pacquée [10] proposed the concept of "structural porosity", which refers to the degree to which a structural system is open to space, as a factor determining the adaptability and flexibility of buildings. Their research primarily focused on typical reinforced concrete column-beam frames and rib-slab grids, demonstrating that structures with more gaps (porosity) between the framework—such as typical column-beam structures or rib slabs—are better suited for future building renovations or flexible spatial use. However, the study does not extend to truss structures or long-span buildings, and the selection of structural systems applicable to new construction or the early design stages is excluded from the research. Instead, it can be viewed as a case study examining the role of structural systems primarily in the context of renovating existing buildings or changing their use.

Previous research has focused on complex buildings such as high-rise structures and hotels, where the structural system often exerts a decisive influence on the architectural form. Hotel architecture typically requires specialized structural systems, such as transfer girders, because it involves placing large-span banquet halls in the lower zones and repetitive small-scale unit rooms in the upper zones. The verification methods in existing research include expert interviews, experimental studies on structures and materials, and the development of structural design models.

Previous studies have focused on cases where structural systems inevitably play a crucial role in architectural design, primarily examining the relationship between exterior form and structural systems.

However, there are very few research cases that identify structural stability factors from the early design stages, select appropriate structural systems, and integrate these with the building’s exterior form and interior spaces.

The testing method used in this study involved identifying stress concentration points using structural analysis software (MIDAS) and examining structural stabilization methods as a solution. Each stabilization method is represented as a structural system.

This study categorizes structural systems into architectural forms and spatial organizations. It aims to identify the stabilizing elements within each structural system and clarify their respective impacts on form and spatial organization.

The significance of this study lies in the fact that the structural requirements for the building envelope and those for the floor plan necessitate different structural systems, and that by considering how to address these structural requirements from the initial design stage, a foundation can be established for integrating the structural system with the architectural design.

1.2 Scope and Methods of the Study

A building maintains its form and position because the structural system that responds to internal stress creates the form, and the load from above and the bearing capacity of the ground are balanced, thereby maintaining its position.

In early modern buildings, technological elements were directly reflected in the buildings due to the development of new materials and connection methods. Kenneth Frampton defined modern architecture in his book Modern Architecture as "a break with historicist styles and a search for a new formal logic" within the technological and social changes following the Industrial Revolution at the end of the 19th century. In History of Modern Architecture, Leonardo Benevolo defines it as the totality of newly emerging architectural thought and practice within the context of changes in technology, social structure, and urban conditions following the Industrial Revolution. He stated that ‘modern architecture’ signifies not only new forms, but also a fundamental shift in thinking, viewing it as the representative concept of architectural movements formed from the late 19th century to the mid-20th century.

In this study, modern architecture is defined as emerging after the Industrial Revolution (late 19th century) and focuses on buildings that actively influenced spatial and formal qualities through the advent of new materials and construction methods, such as iron, glass, and reinforced concrete (mid-20th century).

Buildings that use the skeleton structure method are small-scale buildings, many of which are residential buildings; whereas those that use the truss structure method consist of long-span buildings.

This research method classifies buildings into skeleton and truss structure types, and represents them as free-body diagrams with support points and reaction forces. Free-body diagrams simplify buildings by separating them from their envelopes, serving as a straightforward model for structural analysis, and effectively expressing the effects of reaction forces and loads. Using Midas Gen, this free-body diagram approach examined the stability methods, corresponding forms, and spatial effects at nodal points where the bending moments are concentrated from a system integration perspective.

This program was initially developed within an internal venture of the POSCO Group, and is currently commercialized and distributed by MIDAS Information Technology as a commercial finite element structural analysis program. Both dead and live loads were applied, and the self-weight of the frame was automatically calculated using the analysis program (1.2D + 1.6L).

For the boundary conditions, the reinforced concrete (RC) frame structure employed rigid joints (fixed) to accommodate bending moments at the points of occurrence by utilizing the member thickness or shape. The steel frame structure places the steel members (bars) at the points of axial force occurrence and connects those using pinned joints (fins).

This research is not intended for structural design purposes, but rather aims at system integration between the structural system, architectural form, and architectural design; therefore, numerical analysis was excluded. Such research is expected to yield positive effects by approaching the design process, which is traditionally conducted separately within each architectural discipline, from an integrated design perspective that encompasses both architectural structure and architectural design.

An efficient structure is one in which forces move in the form of structural elements. A structurally efficient form minimizes the generation of bending moments or responds to the generated bending moments through the thickness or shape of the members.

The architectural examples of skeletal structures in this study focused on residential buildings by Le Corbusier and Mies van der Rohe. Primarily, small-scale buildings were selected in which load-bearing walls functioned as rigid diaphragms to ensure stability.

Skeleton structures primarily transfer loads in the vertical direction through the combination of columns and beams, but shear walls are used to resist lateral loads generated on the exterior of the building. The residential building case study in this research was selected based on a structure in which shear walls are installed parallel to the lateral loads, centered around the core. Additionally, examples featuring tapered structural frames were selected, in which the thickness or shape of the members served as stabilizing elements.

While tapered members are primarily used in PEB systems for steel structures, we selected buildings featuring them in skeleton structures—specifically, monolithic structures where the spectator seating and roof are structurally integrated—focusing on examples where the depth of the members is intentionally thickened at points where structural forces are concentrated, such as in cultural and assembly facilities or the interior columns of factories.

For the truss structure building cases, structures used for purposes involving relatively large numbers of people, such as research and exhibition facilities, were selected. The focus was on buildings in which axial forces were the primary stresses, enabling the creation of relatively long-span spaces. Accordingly, we selected case studies that utilized Warren trusses based on triangular grids and Vierendeel trusses based on orthogonal frames to expand spatial freedom and create column-free spaces, as well as a case study that implemented a Space Lattice Truss based on a three-dimensional spatial grid to create a circular plan, and examined the relationship between structure and form.

This study examines how structural engineering expertise influences floor plans and external forms by selecting cases in which structural elements are actively expressed using new materials and construction methods. It also views early modern architecture as the beginning of system-integrated design, where facilities and structural systems are actively expressed in architectural form, much like contemporary high-tech architecture.

2 THE RELATIONSHIP BETWEEN THE DEVELOPMENT OF ARCHITECTURE AND STRUCTURAL SYSTEMS

2.1 The Development of Building Materials and Changes in Structural Systems

Architectural styles change with the sociocultural context, scientific technology of the era, emergence of new materials, and development of construction methods.

Ancient Western architecture used stone as its main material and iron as the connection method. Iron used in the past lacked sufficient tensile strength and was not used as a building material.

The structural system of Greek architecture consists of columns and beams made of stone. They moved beyond past masonry methods to construct magnificent temple buildings. The stone was cut to size, and the individual members were grooved to insert fasteners for use as columns and beams. For buildings intended for large gatherings, such as assembly facilities, a mixed structure was used with wooden trusses for the roof and stones for the walls. Thus, the structural system takes form through appropriate selection and combination according to the scale and use of the space.

Roman architecture is characterized by arches, vaults, and dome structures. It has changed from architecture for the gods in Greece to architecture for people, requiring larger interior spaces than Greek buildings. The material was stone, as in the Greek era; however, the main structural system responded to compressive forces. A representative example is an aqueduct, which is a water-supply system in which continuous arches are stacked in layers.

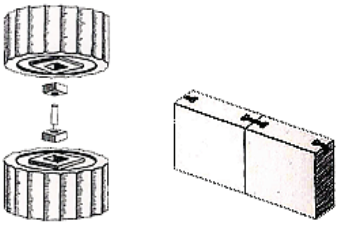


Figure 1 Method for joining columns and beams

The shape of the arch structure causes vertical forces to flow along the curve as compressive forces. Stone is an appropriate material to respond to these compressive forces, and an example of a dome structure is the Pantheon. The interior has a circular plan with a diameter of 43.6M and uses a dome structure for the roof.

Gothic architecture is represented by cathedral buildings, where pointed arches, rib vaults, and flying buttresses were used as structural elements. The pointed arch

can guide compressive forces more vertically, reducing horizontal forces. The rib vault is often seen as the starting point of the Gothic style, and it can reduce the load of the ceiling by concentrating the roof load onto the ribs, which are structural members. A flying buttress is an arch-shaped structural member that prevents the buckling of walls. It distributes the lateral force (thrust) generated on the nave side of the cathedral to the outside.

Gothic architecture can be seen as a case in which a structural solution is rationally applied to symbolically express the Christian faith and the aspiration to rise high towards the heavens. In pre-modernization Western architecture, stone was used as the material, stone units were cut into individual members, and the method of connecting and constructing the members had a significant influence on the structural system and architectural form. With the increase in time and demand, large-scale and unified interior spaces have become necessary, and various construction methods have been applied to create larger and wider spaces. In other words, the main architectural challenge before modernization was creating large interior spaces using stone as the material.

2.2 The Development Process of Modern Architecture and Structural Systems

Ancient Western buildings were mostly temples and cathedrals. Through social transitions, such as the Industrial and civil revolutions, architecture has changed from being for gods to being for people.

The reason for the interest in modern architecture is that it actively applies new construction methods and structural systems to buildings using the new materials of that era: plate glass, iron, and concrete.

19th-century architecture was a transitional period to modern architecture, where the main material, stone, was replaced by new materials such as reinforced concrete and plate glass. The use of steel structures with iron as the main structural frame began in the late 19th century. Early 20th-century buildings used the skeleton structure method with reinforced concrete as the material [11].

A combination of Rahman structures built with columns, beams, and partial load-bearing walls was used. The formal characteristic of such buildings is the repetitive use of forms owing to the modularization of the structural system, and they are often constructed with straight lines rather than curves, considering the workability of concrete.

Late 20th-century buildings used truss structures. Using a truss structure, various stresses occurring in the building are converted into axial forces, thereby reducing the self-weight, and the corresponding members can be thin and long linear elements. This has made it possible to create relatively wide and uniform long-span buildings.

In buildings, structural members typically experience axial forces, bending moments, or a combination of these stresses. Structural members are more efficient when subjected to axial forces than to bending moments. This is because the stress caused by the axial force is distributed almost uniformly across the entire cross-section of the member. This stress distribution allows the entire cross-section to be utilized up to the allowable limit of the material. In contrast, the bending stress distribution exhibited maximum values at the top and bottom flanges of the section and minimum values at the neutral axis. Furthermore, the bending stress requires both the cross-sectional area and the distance between these areas. Therefore, the most critical factor in the design of a bending member is its thickness in the direction of rotation [12].

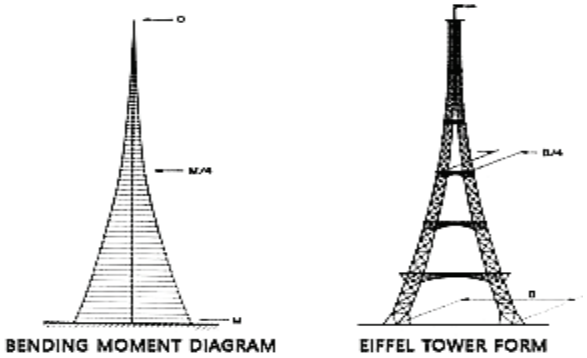


Figure 2 Eiffel Tower response to bending stress

The fact that the bending stress is related to the thickness of the structural member indicates that the bending stress is the primary factor determining the cross-section of the structural member. This is because thickening areas where large moments occur and thinning areas where moments are small naturally form the cross-section of the structural member. In practice, drawing a bending moment diagram based on the loads applied to the structure and shaping the structure yields the form closest to the most rational structural member. For example, drawing a bending moment diagram for wind loads applied to the Eiffel Tower and considering wind loads in both directions revealed that this directly corresponded to the shape of the tower [13].

This study primarily focused on the axial force and bending moment among the various stresses acting on structures. This is because these stresses exert the greatest influence on the cross-sectional shape, connection method, and overall structural form. Therefore, in this study, the stress concentration refers to the support points subjected to high bending moments.

3 STRUCTURAL ELEMENTS AND FORMS IN MODERN ARCHITECTURE

3.1 Skeleton Structure Method

Modern buildings can be divided into skeleton structures, truss structures, and form-active structures, which respond according to the type of structural system.

Each building must have a stable structure. Structural stability refers to the ability of structural members to resist loads while maintaining the form of the structure. Furthermore, a stable structure returns to its original state, even when subjected to minor disturbances, whereas an unstable structure transforms into an entirely different state. Additionally, a building must achieve equilibrium under

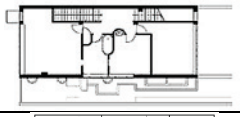
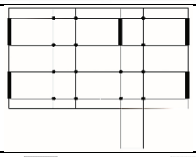
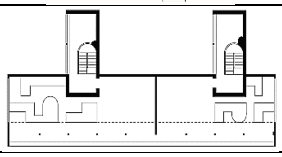
applied loads. Equilibrium implies that all applied loads are precisely balanced by the reaction forces generated at the foundation through the way the loads are transmitted via the internal form of the structure and foundation.

To achieve a stable state, the skeleton structure requires the installation of rigid connections, bracing, or rigid diaphragms. Although rigid connections are highly useful from a spatial planning perspective, they increase the degree of structural indeterminacy [12, p. 23].

The skeleton structure method can be divided into a rectangular-shaped structural method and a tapered-shaped structural method. The rectangular-shaped skeleton structure method consists of a combination of a Rahmen structure made of rigid joints of columns and beams, and load-bearing walls. Its formal characteristics are that vertical and horizontal members are joined at right angles and are composed of linear members, such as columns and beams, and planar members, such as floors, walls, and roofs. The tapered-shaped skeleton structure method responds to the stresses acting on the building with the shape of the members, pursuing appropriate stability, especially at the connection parts where the bending stress is concentrated.

Le Corbusier's dom-ino structural system is a rectangular skeleton structure method that was applied to most residential buildings in the 1920s. A flat slab was used in the lost tile method. A flat slab constructed with lost tiles guides the flow of the load acting on the slab in one direction. The slab sizes of the residential buildings where the dom-ino structure was applied were mainly 5 × 2.5 m and 5 × 5 m [14]. The dom-ino structure allows for the free arrangement of walls on the floor plan because it applies the lost-tile method, which does not require the installation of a ceiling frame. In addition, because the columns and slabs bear the load instead of load-bearing walls, they exhibit a characteristic facade with ribbon windows.

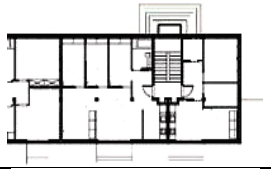
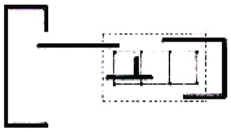
Table 1 Bearing wall and skeleton structure of the domino house

Dom-ino House	Bearing Wall & Frame Structure	Structure System
Guitte house (1926)		skeleton structure + Bearing Wall
Garches house (1927)		skeleton structure + Bearing Wall
Stuttgart-Weissenhof (1927)		skeleton structure + Bearing Wall

The structure of the Mies buildings is a rectangular Rahman structure composed of load-bearing walls, columns, and beams. He also actively used steel materials and employed disjoint in which the connection process of the members was exposed to the external form. It emphasizes the materials that make up the building and the method of connecting members. The connection of the steel members uses a pin joint, which reduces the bending stress at the ends of the members, and the finish is expressed in an external form. Therefore, the emphasis on the connection method shows that Mies's architecture constructed a fluid space using new materials and was distinct from the architectural space before the modern era.

Mies's buildings used members with improved cross-sections. An improved cross-section means using members that are faithful in responding to stress. The Barcelona Pavilion and Tugendhat House used cross-shaped columns and I-beams. The columns used reduced self-weight while performing an appropriate load distribution by welding steel plates where needed and leaving the rest empty.

Table 2 Stabilizing elements of a Mies building

Mies's Residential Architecture	Bearing Wall & Frame Structure	Structure System
Weissenhof Siedlung (1927)		Frame Structure ＋Bearing Wall
Barcelona Pavilion (1929)		Frame Structure ＋Bearing Wall
Tugendhat House (1930)		Frame Structure ＋Bearing Wall

The tapered-shaped skeleton structure method is mainly used for columns and roof shapes, such as those of stadiums, whereas the Stadium in Florence, designed by Pier Luigi Nervi, has a thicker shape at the beginning of the cantilevered canopy than at the end. The length of the long side was 220 m, and it had a rigid joint with a spectator seating slab. The spectator seating slab is inclined according to the viewing direction and acts as a brace.

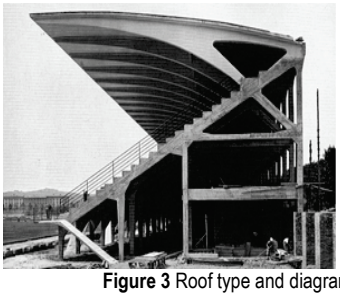
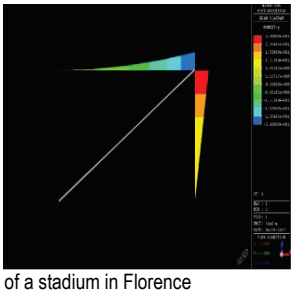



Figure 3 Roof type and diagram of a stadium in Florence

The upper part of the vertical member is the red zone, which corresponds to the region of maximum positive bending moment. The beam-column joint is represented by the blue zone, which corresponds to the region of maximum negative bending moment. In other words, the maximum bending moment of the structure occurs at the beam-column

joint. In the case of skeleton structures, the thickness of the members is increased to achieve structural stability, and in this study, such a configuration is referred to as a tapered structural system.

An example of reinforcement in a column capital can be found in the columns of ancient Greek temple architecture, where an abacus was used as the capital for reinforcement. The internal columns of the Johnson & Wax Building have a wide concentric circular shape in the capital. This is because the bending stress was formed in a concentric circular pattern when the stress flowed from the slab to the column. When columns are joined to a slab, they become load-flow paths, and isostatic lines are formed depending on the column positions. The shapes of these isostatic lines are expressed as waffle slabs or rib bolts.

To elucidate the process of ground and superstructure load transfer in a flat slab system, an analysis of the maximum bending moment distribution revealed that, as loads are applied, severe stress concentration occurs around the column capitals. This is visualized in the diagram as a circular contour pattern of red and orange lines centered on the columns. This area forms the structurally most vulnerable critical section within the slab system. It is at risk of punching shear failure, where the column pierces through the slab. Therefore, enlarging the column capital in a concentric circular pattern ensures structural stability against punching shear forces and directly visualizes the stress distribution.

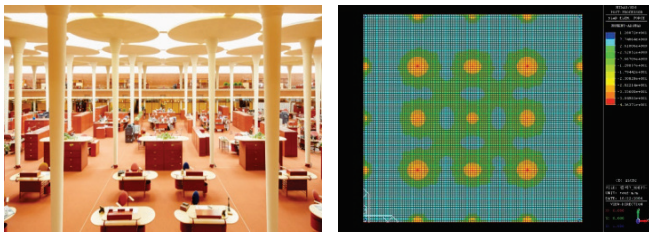


Figure 4 Capital shapes and column diagrams

The tapered shape of the pilotis columns was well expressed in the 1958 Berlin housing complex. The tapered legs that leaned into the building and columns that leaned out of the building were arranged repeatedly. A bending moment that rotates outwards occurs. Therefore, an axial force towards the inside occurs in the cantilever beam. This inward axial force is countered by the pilotis columns that are inclined outwards. The outward bending moment generates an outward axial force in the cantilever beam. To respond to this axial force, pilotis columns inclined inward were used, and the intersecting column shapes of the same structure were related to wind loads.

The cantilever structure was analyzed in two scenarios: one where the vertical load is applied at the outer end of the cantilever and another where it is applied at the inner end. Since both cases inevitably generate horizontal thrust, the direction in which the column tilts directly affects the configuration of the upper beam and the column.

When a vertical load occurs inside the cantilever, a rotational force toward the interior is generated at the joint between the beam and the column. Consequently, a horizontal thrust toward the exterior is generated in the horizontal direction of the beam. Therefore, a column configuration that leans inward is structurally advantageous. When a vertical load is applied to the outer end of the cantilever, a thrust is generated toward the interior of the beam, making it advantageous for the column to be inclined outward. In this way, the forces exerted by the inward-leaning and outward-leaning columns—pushing and pulling the beam outward—cancel each other out across the entire planar structure, allowing the building to withstand lateral drift, such as tilting to one side or spreading outward.

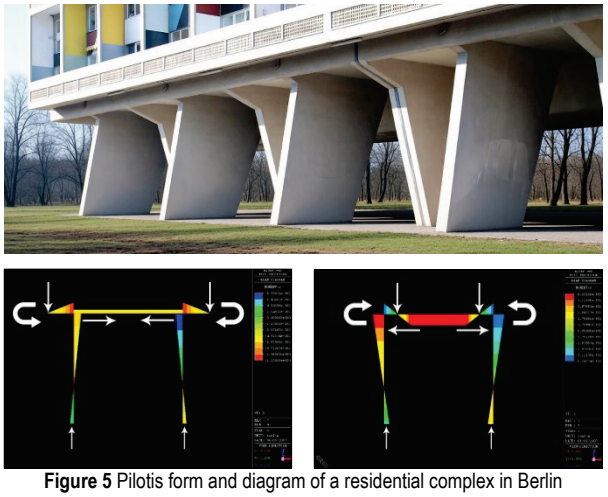


Figure 5 Pilotis form and diagram of a residential complex in Berlin

Table 3 Taper-shaped skeleton structure

Building Name	Structural System
· Hat Factory of Herrmann Company, Erich Mendelsohn, Paris, France, 1921-23	Skeleton Structure
· Stadium in Florence, Pier Luigi Nervi, Florence, Italy, 1930-32	Skeleton Structure
· Johnson&Wax Building, Frank Lloyd Wright, Wisconsin, USA, 1939	Skeleton Structure
· Stadium in Caracas, Villanueva, Venezuela, 1949	Skeleton Structure
· The Unesco Building, Pier Luigi Nervi, Paris, France, 1953-58	Skeleton Structure
· Unite d'Habitation, Le Corbusier, Berlin, Germany, 1958	Skeleton Structure
· Planalto Palace, Oscar Niemeyer, Brasilia, Brazil, 1960	Skeleton Structure

3.2 Trussed Structure Method

A truss is a simple strut assembly with pinned joints and triangular configurations that is subjected to tensile or compressive stresses [15]. The Vierendeel truss can be considered as an example of improving efficiency by altering the internal shape of members to remove portions of the cross-section in areas with low stress. In other words, by considering the stress distribution and eliminating low-stress areas from the cross-section or axial shape of the members, the efficiency of cross-section utilization is enhanced [12, p. 49].

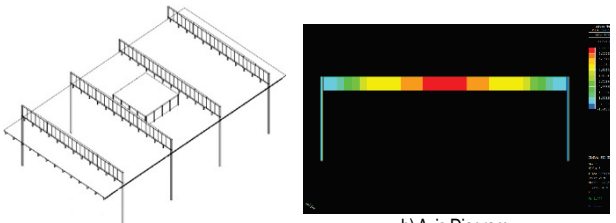
The advantage of truss structures over other form-active structures is that they generate only axial forces even without special shapes [12, p. 51]. Structures that generate only axial forces allow for reduced member thicknesses; when

members are arranged along the load path, no bending moments occur, making them structurally efficient.

Representative buildings using the truss compression structure method are Mies' Crown Hall and Buckminster Fuller's US Pavilion at EXPO 67. Crown Hall realized a column-free space inside. To achieve this, it used a construction method in which the roof was suspended and supported by lateral plate girder installed on the roof as the main structure. Four plate girder are installed and supported by two H-beam columns. In the detailed connection method, the roof purlins were joined to the bottom of the trusses using a shear connection method. The span of the columns was 18.3 m, and the load transmitted from the mullions at 3 m intervals was effectively distributed through the roof trusses. Using a glass wall, the interior appears transparently penetrated, and a column-free space can be created inside, realizing the concept of a universal space.

The roof structure used in Crown Hall is a portal moment frame system that combines plate girders with perimeter columns. It is structurally similar to a Vierendeel truss in that the column-head joints are designed as rigid joints to resist bending and shear, thereby creating a column-free interior space.

The stability of the plate girders is ensured by connecting them to purlins at their lower ends, thereby safely distributing the roof load. The 11 purlins used in the roof distribute the load to the plate girders connected above and transfer it to the H-shaped columns installed at both ends. The stiffeners of the H-shaped columns are aligned with the building's longitudinal direction to prevent overturning.



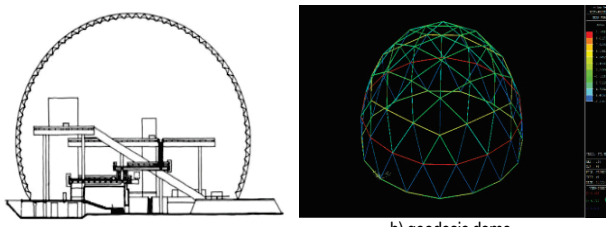
a) Roof truss b) Axis Diagram

Figure 6 Roof truss and stress diagram of Crown Hall

Buckminster Fuller's US Pavilion at EXPO 67 is a geodesic dome in which triangular trusses are repeatedly joined to convert all stresses occurring in the dome into axial forces. It is a dome structure with two layers consisting of an outer layer using triangular trusses, an inner layer with hexagonal trusses, and a web structure that connects the inner and outer layers. The final dome shape had a diameter of 76m and a height of 60.8m, and the structure used tubular steel connected by nodes [16]. The longitudinal compressive and transverse tensile forces of the dome were countered using triangular trusses.

The results of the diagram analysis show that, since the nodes of the geodesic dome structure are pin-connected, no bending moments occur. Therefore, all members can be composed of a combination of straight and diagonal members and are subjected to compressive and tensile forces.

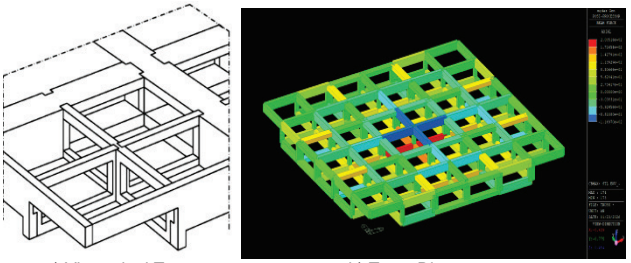
The hoop members at the bottom of the dome structure, shown in red, are subjected to maximum tensile force. Consequently, the diagonal members—which serve as vertical supports connecting the foundation to the lower hoop members—experience maximum compressive force and are shown in the darkest blue on the diagram. The remaining ribs and diagonal members are arranged to form the dome's shape and are shown in yellow or green, indicating sections where tensile and compressive forces coexist.



a) Dome structure cross-section b) geodesic dome

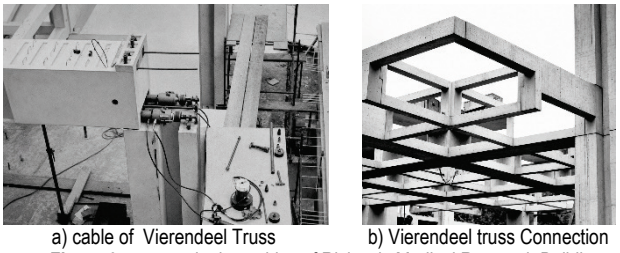
Figure 7 Dome structure and cross-section of the US Pavilion at EXPO 67

As examples of using a Vierendeel truss structure, Louis I Kahn's Richards Medical Research Building and Salk Institute Laboratory Buildings use post-tensioning methods and precast concrete to create column-free spaces inside the laboratories. The floor plan of the Richards Medical Research Building comprises five laboratories, two auxiliary laboratories, and a service cluster that includes ventilation ducts and stairwells. Each laboratory cluster was supported by eight columns, and the slab was constructed using four transverse Vierendeel precast concrete beams. The slab at the end is cantilevered. The Vierendeel truss section was exposed at the end cantilever in the laboratory and constructed using the disjoint method. The interior of the post-tensioned beam accommodates the service piping, and the structural system, service system, and space are mutually integrated. The integration of service facilities through structural systems is a common feature in most of Kahn's buildings [17].



a) Vierendeel Truss b) Truss Diagram

Figure 8 Truss of Richards Medical Research Building



a) cable of Vierendeel Truss b) Vierendeel truss Connection

Figure 9 post-tensioning cables of Richards Medical Research Building

The girder used in the building employs a Vierendeel truss structure. Since there are no diagonal members, the structure resists loads through a combination of bending moments and shear forces supported by the rigid joints.

The lower central section shown in the diagram is marked in red, indicating where the maximum bending moment is concentrated. In contrast, the upper central section is marked in dark blue, indicating where the maximum compressive force occurs. The remaining internal frames, which serve as stress transfer and moment distribution zones, are shown in orange and yellow.

To counteract the central section of the Vierendeel truss, post-tensioning cables are inserted into the truss using the post-tensioning method.

Table 4 Buildings and structural systems using truss structural methods

Building Name	Structural System
· Eames House, Eero Saarinen, California, USA, 1945-47	Truss Structure
· Ford Rotunda, Buckminster Fuller, Michigan, USA, 1953	Truss Structure
· IIT Crown Hall, Mies van der Rohe, Chicago, USA, 1956	Truss structure + Plate Girder
· Richards Medical Research Building, Louis I Kahn, Pennsylvania, U.S.A, 1957-64	skeleton structure + Vierendeel truss
· Salk Institute Laboratory Buildings, Louis I Kahn, California, U.S.A, 1959-65	Bearing Wall + Skeleton Structure + Vierendeel truss
· US Pavilion at EXPO 67, Montreal, Canada, 1967	Truss Structure

4 STABILIZATION METHODS AND ARCHITECTURAL UTILITY IN MODERN ARCHITECTURE

4.1 Structural Systems for Form

The ultimate goal of a building's structural system is structural stabilization. The structural stability can be divided into external and internal equilibria. External equilibrium refers to the state in which stress from above is transmitted along the main structural members to the foundation and subgrade, and the reaction at the foundation balances the upper stress, meaning that it maintains its original state when an external disturbance occurs in the balanced building [13, p. 33]. Internal equilibrium occurs when the strength and stiffness of the members can withstand the internal forces generated within the structure.

The truss structure is a structural system used for roofs. The truss structures for roofs include lattice trusses and geodesic dome structural systems. Both structural systems distribute loads through a triangular structure and respond to the stresses generated on the roof as axial forces. The lattice truss mainly connects relatively short spans within 10m and is constructed in a linear form. The geodesic dome connects relatively wide spans and exhibits a curved shape. Such structural systems respond to axial forces, adopt a disjoint connection method, express details in a technological form, and describe the construction process.

This space is often used for facilities such as exhibitions or assembly halls that require a wide span and a uniform space without columns. The skeleton structure method uses a tapered structural system. The tapered-shaped skeleton structure secures structural stability in places where stress is concentrated to respond to the stress. A tapered-shaped skeleton structure is used in places where stress is concentrated, such as the connection part of columns and beams or the roof end of stadium spectator stands. The member connection method followed the rigid-joint connection method. The joint method visually conceals the connection points and thickening areas where the bending moments concentrate, and conforms to the shape of the bending moment to form the structure.

4.2 Structural Systems for Space

Structural systems for space include the rectangular-shaped skeleton and Vierendeel truss structures. The rectangular-shaped skeleton structure is used as an important structural system for residential architecture as a dom-ino system. In terms of spatial composition, it secured views by placing load-bearing walls on the sidewalls of the residential building and pursued efficiency in the plan composition and spatial arrangement.

A dom-ino slab was placed in the interior space to dimensionalize the residents' range of activities.

This dom-ino structural system has a rectangular form, and the connection of the members adopts a joint method that is not exposed to the outside, thereby influencing the aesthetic form composed of linear elements.

In residential buildings, torsion occurs under horizontal loads depending on the core placement. The location of load-bearing walls or bracings can be determined to minimize torsion while considering architectural planning and space utilization. It is advantageous to position load-bearing walls parallel to the direction of the horizontal loads, and longer walls are more effective than shorter walls.

The rectangular skeleton structure buildings used by Mies employed members with improved cross-sections, such as H-beams and I-beams. Individual members were connected in a disjointed manner and primarily used as columns. Mies pursued a multipurpose space that was diverse, flexible, and flowing. Early residential buildings used load-bearing walls, making it impossible to use large, wide windows; however, as columns and walls were separated, it became possible to construct a fluid space.

The H- and I-shaped steel columns have flange directions aligned with the structural axis. Therefore, the moment connections in the flange direction are structurally advantageous. When steel columns are continuous, the direction of maximum load is often designated as the structural axis. When the columns are arranged discontinuously, the direction of the asymmetry is frequently designated as the structural axis.

The Vierendeel truss, primarily used in Kahn's buildings, serves as a structure for beams, supporting spans of approximately 9 m in laboratories and providing a square-shaped laboratory space. A truss structure for a beam is created by connecting the upper and lower chords using H-beams or I-beams and connecting the two members with braces. This type of truss structure is advantageous in terms of its self-weight because it is lightweight. Moreover, because there is almost no bending stress, the volume of the members can be reduced.

The Vierendeel truss structure is a representative truss structural system for beams with a compressive force at the top and tensile force at the bottom. Reinforced concrete was used for the upper and lower members, which were connected using rigid joints. This is structurally efficient because it distributes and reduces the bending stress inside the members. The spaces in which they were used were mainly places that required a relatively long span of space, such as laboratories or research facilities.

In structural systems for space, the efficient placement of load-bearing walls, the use of steel members with improved cross-sections, and trussed beams are used as elements of stability. In structural systems for space, a structure acts as a medium between spaces. This case differs from pre-modern architecture in that technology directly influences architectural form and space owing to the development of materials and structural systems.

5 CONCLUSION

Architecture has evolved with changes in building materials, joining methods, and structural systems. Advances in structural systems have led to the development of new spaces and forms.

Modern architecture requires relatively large and uniform interior spaces to meet social and cultural needs. Constructing such spaces requires structural elements such as slabs and roofs, with roofs particularly influencing the form of the buildings. Particularly in early modern architecture, building forms were heavily influenced by geometric shapes suitable for steel or reinforced concrete structures. Therefore, early modern buildings are viewed as the origin of contemporary high-tech architecture, which actively exposes structural engineering projects to their external forms.

This study categorizes structural systems into structures for form and structures for space.

Structures for form include truss structures for roofs and tapered frame structural systems. Truss structures for roofs comprise lattice trusses and geodesic domes. The material used was steel, and the connection method employed a disjointed approach, exposed externally, to effectively express the formative characteristics by utilizing fin joints. Lattice trusses combine upper and lower chords to form triangular or square grid patterns, functioning as linear support systems that are used as girders. Geodesic dome trusses combine triangular grids to expand into curved surfaces, thereby creating large-span shell-shaped roofs without intermediate supports. The stability elements of a structural system primarily place the members under axial force conditions. Lattice trusses primarily achieve stability through the arrangement of two-dimensional members by combining bending and axial forces. Geodesic domes achieve stability through three-dimensional curved surfaces and triangular lattices.

Structures designed for this form include tapered-frame systems. They are also called form-active structures and represent the most natural form of response to stress flow, conveying visual stability. The connection method uses joints to ensure that connection points remain concealed. Structural stability is achieved by thickening sections where stress is concentrated, or by arranging members along the load flow paths.

Structures for space include right-angled frame systems and Vierendeel truss structures applied to girders. The rectangular-frame structure efficiently positioned the load-bearing walls to secure daylighting and views, with the walls acting as rigid diaphragms to provide structural stability. Their interior use was predominantly residential. Furthermore, when steel members were used, improved cross-sections were employed by removing sections with low stress, considering the stress distribution. This reduced the self-weight of the members and enhanced their structural stability. Vierendeel trusses eliminate the central portion of the girder because maximum stress occurs at each end. Furthermore, because the bending moments were concentrated in the central section of the Vierendeel truss girders, prestressing was applied to achieve structural stabilization. This system has been applied to interior spaces that require relatively long spans, such as exhibition halls or laboratories.

Buildings constructed using the skeleton structure system employ tapered members and shear walls as stabilizing elements. Tapered structures are primarily applicable to the roofs of buildings requiring long spans, such as auditoriums and assembly halls. Additionally, shear walls serve as stabilizing elements that bear vertical loads while resisting horizontal forces. This system is primarily used in residential buildings, and structural stability is achieved by arranging shear walls parallel to the horizontal forces. Therefore, for buildings with rectangular floor plans, such as residential structures, it is advantageous to prioritize the skeleton structure system; furthermore, incorporating tapered cross-sections allows the structure to adequately resist bending moments.

Buildings using a truss structure minimize bending moments and ensure structural efficiency by directing axial forces into the primary stress system. Through the repetitive combination of linear members, they simultaneously achieve structural stability and architectural form. Therefore, for circular floor plans or when column-free interior spaces are required, prioritizing an appropriate truss system will enable efficient integrated design.

This study examined how the stabilizing elements of skeleton and truss structures influence the form and spatial design of buildings, focusing on early Modern architecture. However, the study has limitations in that the case studies were confined to combinations of two-dimensional linear members and some three-dimensional lattice trusses, and thus did not fully encompass the mechanical behavior of the various non-standard curved surfaces and column-free spaces found in contemporary architecture. To address this, future research will build upon the methodology of this study and focus on large-scale, column-free buildings by analyzing three-dimensional stress flow. Specifically, we plan to investigate how form-active and surface-active structural systems—such as cable, membrane, and shell structures—control and interact with spatial and exterior forms.

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