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# Forces, Structures, and the Evolution of Natural and Artificial Forms

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***Abstract –*** The formation of architectural form is influenced by functional, economic, social, cultural, climatic, and environmental factors, along with construction and stability conditions. Stability is crucial in shaping form and ensuring durability against environmental factors, as it guarantees the structural integrity of architectural form. Thus, the role of structure in design and its impact on form warrants thorough investigation. Understanding the development of structural knowledge elucidates its historical relationship with architecture. While form is often seen as the manifestation of architecture, its creation is inherently linked to structure, with structural concepts and methods pivotal in generating form.

This article examines the structural aspect of form, focusing on the system of load distribution, force behavior, and transmission methods. It questions how forces influence form formation. The descriptive and analytical research method aims to provide a novel perspective on the relationship between structure and architecture to enhance structural understanding among architectural engineers. By tracing the roots of structural knowledge and analyzing natural forms and force flows in materials and artificial forms, the study seeks to achieve a logical design process for form in the architectural context, considering complex structural concepts.

*Keywords – Architectural Form, Structural Resistance, Natural Forms, Force Flow, Form Formation, Bending.*

## I. INTRODUCTION

The correlation between structure and architecture in the design context has been a focal point of research for numerous architects and structural engineers over the last six decades. An important obstacle in this domain has been the absence of essential structural knowledge among architects, which is vital for efficient building design. It is crucial to improve the architects' understanding of structural concepts, and it is imperative to develop effective strategies to achieve this. This article offers a novel viewpoint on the correlation between structure and architecture to improve architects' comprehension. The article clarifies structural concepts for better understanding by examining the historical process of this relationship and introducing force as an operative system.

Previous research has shown that architects consistently encounter difficulties comprehending structural concepts because there is a lack of comprehensive frameworks that effectively incorporate structure into architectural practice. The absence of a comprehensive and unified resource for teaching structural courses in architecture has highlighted the significance of the subject matter discussed in this article (Addis, 2019; Balmond, 2017; Billington, 1983).

The article employs lucid and unambiguous language, rendering it easily comprehensible to architects while emphasizing the significance of content and conceptual coherence. It aims to connect meaningfully with architects by presenting foundational concepts that help understand structural behavior, particularly by exploring natural patterns. Hence, intricate mathematical equations and force analyses generated by software are deliberately omitted to avoid overwhelming the reader.

Historically, buildings have consistently integrated structural systems to guarantee stability against various forces, including weight, wind, and earthquakes (Ching, 2014). Throughout history, humans have been required to build sturdy and secure structures, using different materials to shield them from destructive forces and to understand and manage the forces that affect their architectural designs. The Earth supplies all construction materials and produces gravitational forces due to gravity. Furthermore, climatic conditions and geological structures generate lateral forces, such as wind and earthquakes, as well as forces of contraction and expansion. Architecture must consider various factors beyond functionality and strength in construction. These factors include economic considerations, environmental conditions, time constraints, etc. (Salvadori, 2002; Schodek et al., 2014; Allen & Iano, 2019).

Hence, the design and construction of a building are shaped by a range of factors and variables, with the structural framework playing a vital role. The loads and forces in a building play a crucial role in determining and shaping its structure. Therefore, it is crucial to study the magnitude of loads and comprehend how they influence the creation of architectural structures. The structure of a building, much like the human skeleton, provides stability, durability, and cohesion to the various components and architectural forms, ensuring the overall integrity of the building. Therefore, it is crucial to regard structure as an essential component of the comprehensive architectural design process. Architects must acquire knowledge of the principles of this discipline to successfully incorporate them into creating architectural spaces (Gartshore and Mayfield, 2016; Macdonald, 2001).

While some may perceive structure as a constraint on an architect's design abilities, the wide range of structural solutions actually enhances the potential for innovative designs. This article examines the point where structure and architecture intersect, providing a thorough analysis to improve comprehension and implementation of structural principles in architectural design.

## II. MATERIALS AND METHOD

The research utilized various materials to investigate the correlation between structural forces and architectural forms: Historical and Contemporary Texts: An extensive selection of texts authored by classical and modern architectural theorists and practitioners served as a basis for comprehending structural principles and their influence on form. Examples of specific instances or situations: A selection of architectural works was analyzed to gain insight into the practical application of structural principles and their impact on form. Observations of Natural Form: The study focused on examining natural forms and their structural efficiencies to identify similarities and extract principles that can be applied to architecture. Structural models, diagrams, and computer simulations were employed to visually represent and examine the behavior of forces in diverse forms and materials. Scholarly articles and journals, which undergo a rigorous peer-review process, offer valuable insights into the latest advancements and theoretical developments in structural engineering and architecture. Approach The approach employed in this study was both descriptive and analytical, with a specific focus on examining the relationship between structure and form in architecture: The literature review encompassed a comprehensive examination of various sources, including architectural treatises, engineering texts, and case studies of notable works. It aimed to provide theoretical perspectives and historical context on the correlation between structure and form. The case study analysis examined architectural projects renowned for their innovative structural solutions. It provided a detailed exploration of how structural considerations significantly shaped the architectural form of these projects. A comparative analysis examined the structural efficiencies of natural and architectural forms. The study focused on load-bearing mechanisms and material properties to identify how nature can inform architectural design. Simulation and Modeling: Computer simulations and structural modeling were employed to examine the force dynamics in various architectural structures, enabling the visualization of load distribution and deformation under different circumstances. The descriptive analysis involved examining literature, case studies, and simulations to identify important patterns and principles in the interaction between structure and form. An analytical framework was created to incorporate structural principles into architectural design. This framework offers architects a methodical approach to considering structural forces when generating forms. These materials and methods were designed to thoroughly comprehend the crucial function of structure in determining architectural form. This would enhance the structural expertise of architectural engineers and encourage an integrated design approach that considers both aesthetic and structural necessities.

## III. HISTORICAL DEVELOPMENT AND FORMATION OF STRUCTURAL ENGINEERING

The historical development and formation of structural engineering refers to the evolution and establishment of the field that deals with the design and construction of structures.

The evolution of construction and its changes have predominantly been an exploratory endeavor. Over time, people's attention was gradually drawn to the significance of strength, durability, and stability due to the accumulation of experiences. Experience has significantly influenced the advancement and comprehension of the science of building, similar to its impact on other fields like medicine and astronomy (Timoshenko, 1953). As a result, construction grew in size and importance, resulting in the development of a separate field of study called structural engineering, distinct from mathematics and mechanics (Billington, 1983).

Table 1. Historical development and formation of structural engineering

| Period | Key Developments | Impact |
|---|---|---|
| 1400 BCE | Construction of ziggurats and pyramids | Early significant structures with basic load-bearing techniques |
| 287-212 BCE | Archimedes formulated the law of levers | Introduction of fundamental mechanical principles |
| circa 365-275 BCE | Euclid established geometric principles | Application of geometric principles in construction |
| 15th-16th Century | Leonardo da Vinci documented initial findings on material strength | Foundation of experimental methods in material science |
| 17th-18th Century | Contributions by Galileo, Robert Hooke, Isaac Newton, Thomas Young, and Siméon Denis Poisson in the mechanics of materials | Development of the scientific methodology for load transfer and material strength |

The shift of humanity from natural shelters to constructed shelters presented challenges about longevity and sustenance. Early structures were characterized by their simplicity and had basic designs due to their limited stability and durability knowledge. The initial remarkable edifices featuring substantial architectural designs were ziggurats and pyramids, constructed around 1400 BCE. These structures exhibited limited advancements in their construction techniques and were primarily erected for specific functions, such as political or religious purposes. The reference is from Salvadori's work published in 1980. Despite their considerable height, these structures presented significant load-bearing difficulties. The solutions employed were rudimentary, relying on the utilization of massive and weighty materials and substantial energy consumption during their construction.

Initial construction patterns were superficial imitations of nature and could not be expanded or adjusted. Nevertheless, this trend transformed as time passed. Archimedes (287-212 BCE) formulated the law of levers, while scholars such as Euclid (circa 365-275 BCE) established geometric principles. Over time, as these principles progressed, they were implemented in construction. The evolution of load-bearing systems using various materials was driven by the development of algebra and mathematical formulas, technological advancements, the emergence of new materials, and human needs. This led to innovations and the establishment of structural principles (Addis, 2008; Mark & Hutchinson, 2014).

Before the late 16th century, humans possessed limited knowledge about the properties of materials, lacking precise and universally applicable scales and measurements. Further endeavors resulted in the precise identification of the properties of different substances and enhanced human capacity to utilize them. Many inquiries arose concerning the ability of materials to bear loads and the mechanisms by which they do so, which ultimately led to the emergence of the field of mechanics of materials (also known as strength of materials). This event signified the initiation of the scientific methodology towards the transfer of loads and the flow of load-bearing. Leonardo da Vinci (1452-1519) recorded the initial outcomes achieved from the study of the mechanical properties of materials using practical observation and systematic testing. During the late 16th century, Galileo (1564-1642) conducted a thorough study of this subject. However, the understanding of the relationships involved remained incomplete until further contributions were made by mathematicians and physicists such as Robert Hooke (1635-1703), Isaac Newton (1642-1727), Thomas Young (1773-1829), and Siméon Denis Poisson (1781-1840) (Timoshenko, 1953; Sadhu Singh, 2003). Therefore, the knowledge that originated from firsthand experience was refined and developed into the field of structural science by utilizing experiments, algebraic methods, and analytical techniques.

Load transfer systems have been created, and the theoretical behavior of materials and structural components can be determined thanks to our comprehension of forces and their analysis. In addition, progress in computer technology has enabled the analysis of structural behavior before construction (Harris & Sabnis, 1999). Structural engineering focuses on analyzing the origin, spread, and distribution of forces and studying the behavior of materials and their ability to bear loads. Structural engineering has become a specialized discipline that supports scientific advancements and allows architects to enhance and enlarge the size and quality of their buildings, thereby promoting architectural innovations (Ching, 2014). Nevertheless, one must consider how architects can effectively employ their understanding of structural principles and what influence structure has on the design of buildings. To address these inquiries, the connection between structure and architecture, as well as the interplay between these two fields, is examined by utilizing available resources and documentation (Gartshore & Mayfield, 2016; Macdonald, 2001).

## IV. LITERATURE REVIEW

Multiple sources examine the correlation between structure and architecture, authored by experts from both disciplines actively involved in professional practice or academic teaching. The sources encompass a range of topics, including educational aspects of structures, the integration of structure and architecture, collaboration between architects and structural engineers, understanding the behavior of structures, and the history of construction (Allen & Zalewski, 2010; Ching, 2014). To effectively use structural knowledge, it is imperative to first attain the requisite comprehension. Within these sources, it is necessary to analyze forces' behavior, shape, and action. This should be followed by thoroughly examining the most important forces that have a major impact on structural stability.

In his book "Building Forms," Mehdi Farshad explores the fundamental concepts and definitions of building forms, the criteria for evaluating them, the evolutionary process of their development, and strategies for attaining complete or optimal forms (Farshad, 1974). The author examines multiple structure and design aspects, classifying structural forms according to their geometric and physical properties. Additionally, the author clearly explains fundamental structural principles and different types of forces.

Edward Allen's book "Form and Forces" seeks to streamline intricate architectural forms, examine the influence of forces on structures, and elucidate the distribution of forces within forms (Allen, Zalewski, & Boston Structures Group, 2010). The primary focus of this book is to compute forces through the utilization of graphical techniques. He mediates discussions between structural and architectural experts to elucidate their collaboration in creating architectural forms based on structural solutions.

In their book Finding Form, Mahmoud Rasch and Frei Otto analyze structures molded by natural forces. They aim to discover shapes that evolve in the surroundings and are enhanced through natural forces (Otto & Rasch, 2001). Their research studies natural entities, including living organisms and non-living objects. They conduct experiments to develop practical forms that humans can use, using the principles of natural formation.

Mario Salvadori's book "Structure in Architecture" aims to elucidate the role and significance of structure in architecture without relying on formulas. The author seeks to simplify complex concepts and illustrate how fundamental principles influence structural decision processes (Salvadori, 1986). These sources emphasize the creation of shapes through the application of forces. By applying the principles and rules of structural science or by utilizing experience and experimentation, architects strive to elucidate and regulate the process of creating architectural forms. The challenge architects encounter is not limited to the physical structure alone but rather requires a thorough comprehension of it, which ultimately improves the quality of the design.

## V. ELUCIDATION OF THE CORRELATION BETWEEN STRUCTURE AND ARCHITECTURE

The literature on the correlation between structure and architecture, authored by experts from both disciplines, emphasizes that this matter is a shared concern for both scientific domains. Hence, to accomplish the intended design objectives, it is necessary to have the cooperation of both disciplines. Collaboration requires the combined effort of skilled professionals who have the necessary design expertise and abilities, as well as a willingness to work together (Charleston & Pirie, 2009). The relationship between architectural and structural design solutions is highly interdependent and indivisible, as the effectiveness of one directly impacts the effectiveness of the other. This statement is in accordance with Vitruvius's assertion that architecture should exhibit structure, functionality, and aesthetic appeal (Fahmi et al., 2012).

The distinction between architectural engineering and structural engineering has emerged over three centuries.

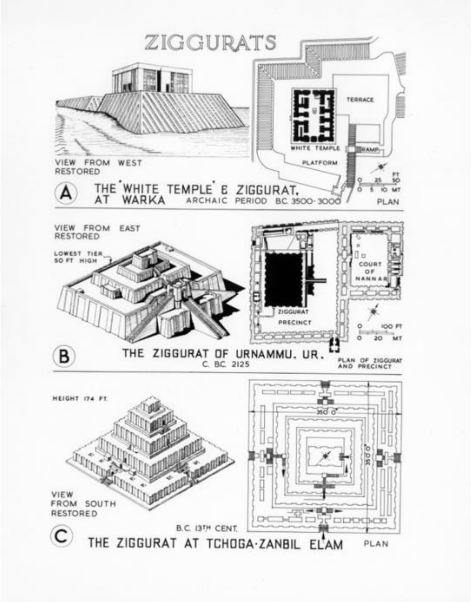

Fig. 1 Examples of early Mesopotamian architecture: Ziggurats (A-C): plans and aerial perspectives
Sources:https://www.ribapix.com/examples-of-early-mesopotamian-architecture-ziggurats-a-c-plans-and-aerial-perspectives_riba100766

Historically, architecture was executed by skilled artisans with expertise in multiple trades and industries. Over time, their varied construction experiences evolved into sensory techniques for implementing and comprehending the effects of forces in creating forms. Various construction specialties have become distinct over the past three centuries due to social, economic, and political changes. These changes include the Industrial Revolution, new intellectual movements, urban growth, and expanding various knowledge domains (Addis, 2008). However, today, architects coordinate multiple construction specialties, necessitating a comprehensive understanding of each specialty. An architect encounters various quantitative and qualitative challenges in the design process that require attention. However, their proficiency in addressing these challenges may vary. Due to the extensive nature of most projects, architects cannot often oversee all the intricate aspects of specialized tasks. One of the concerns pertains to the safety and security of the building, which the architect cannot ensure; this responsibility falls under the purview of the structural engineer. Architects solely focus on overarching structural matters, specifically those that establish the connection between form and structure. Nevertheless, they must possess a comprehensive understanding of the fundamental principles of structures, load distribution, and their influence on the overall shape of the edifice.

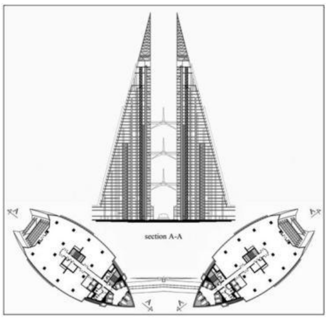

Fig. 2 Bahrain World Trade Centre: Floor plan and section integrated architectural and structural design solutions, such as modern skyscrapers

Source: https://www.mdpi.com/2075-5309/9/9/193

Architects should comprehensively comprehend the basic principles of structure, including its rules and grammar, to effectively tackle force-related problems using a sensory approach (Moore, 1999).

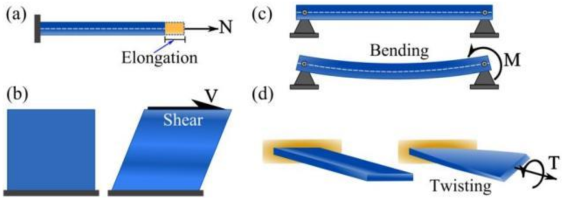

Fig. 1 basic principles of structures such as load distribution, types of forces, and structural integrity.

Source: https://engcourses-uofa.ca/books/statics/internal-forces/types-of-internal-forces-and-their-diagrams/

## VI. STRUCTURE AND FACTORS AFFECTING ITS FORMATION (STRUCTURAL PREREQUISITES)

Within the field of architectural engineering, the term "structure" pertains to the systematic interplay of forces that guarantee the stability and robustness of a building. According to the Oxford Dictionary (2020), it defines it as the connection or association between the different parts or elements of an object, organized quality, building, or any complex entity. It also refers to the connections or interactions between the components of a group that can be observed. This definition emphasizes the importance of structure as a vital element in preserving a building's strength and efficiency.

The structural system of a building is essentially the configuration of forces that equilibrate and disperse external loads and internal reactions. The primary purpose of structural engineering is to guarantee the stability and safety of a building in different circumstances (Ching, 1995). Structural engineering is a field that integrates comprehensive understanding of structural principles, materials, construction details, construction processes, and analytical techniques (Allen, Zalewski, & Boston Structures Group, 2010).

Salvadori outlines several fundamental prerequisites for a structure, namely: equilibrium, steadiness, robustness, efficiency, cost-effectiveness, and configuration (Salvadori, 1986). Balance, the paramount element of statics, pertains to the condition of equilibrium and absence of movement in a structure's entirety and components. When the forces acting on an object are equal in magnitude and opposite in direction, the object will remain stationary in all directions, which is referred to as a state of equilibrium. The presence of equal and opposite forces results in a state of balance, where both the external and internal reactions of the object are in a state of equilibrium (Moore, 1999).

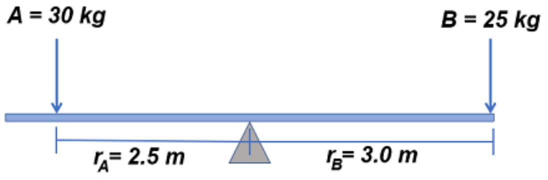

Fig. 3 A balanced structure or a seesaw illustration showing equilibrium, with forces acting on an object that remains stationary.
https://study.com/academy/lesson/static-equilibrium-of-rigid-bodies.html

Strength in a structural element, in relation to internal forces, pertains to the absence of defects in the components and their capacity to withstand the applied loads. The concept mentioned here refers to the ability of a structural element to resist external forces, and it is directly linked to the structure's material properties (Muttoni, 2011). Stability refers to a building's ability to withstand external forces without its components disintegrating, which is also known as geometric stability. Geometric stability pertains to the quantity and characteristics of connections, such as simple or roller connections, as well as intricate joints, and how they are utilized.

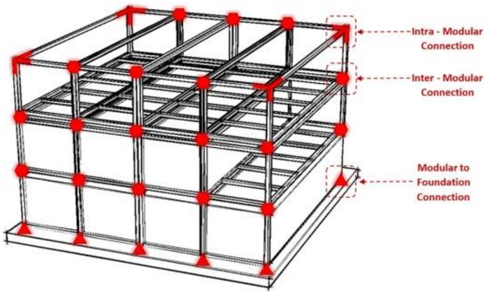

Fig 4. Diagram of a stable building structure, https://www.sciencedirect.com/science/article/pii/S2352012421008262

In addition, there is a concept called resistant stability, also known as internal stability. This refers to the ability of material particles to bear loads when subjected to external forces (Allen et al., 2010).

The performance of a structure is determined by its optimal load-bearing capacity, ensuring that the structure is neither excessively nor insufficiently designed, and that materials are utilized efficiently. The force shaping determines the structural form. For instance, an arch is appropriate for compressive loads, while a straight line is suitable for tensile loads (Salvadori, 1986). Economy is a fundamental necessity in a structure, characterized by the efficient flow of forces and the absence of unnecessary design elements. While structural efficiency is an important consideration, it is also crucial to take into account other factors such as production, control, and construction when choosing a structural system. The economic performance of a building is determined by the technology that is available for use and the speed at which the construction process takes place. The development and formation of structural systems are primarily influenced by the efficient transfer of forces, the optimal utilization of materials, and the consideration of economic and architectural factors (Gartshore & Mayfield, 2016).

Structure is a vital component of design and plays a pivotal role in creating form. Therefore, the structural form is regarded as one of the fundamental elements of the structure. The structural form entails the deliberate manipulation of shape and size to optimize the transmission of forces within a given structural system, resulting in an aesthetically pleasing outcome. These forms have a visually pleasing and powerful effect. Designers frequently draw inspiration from the numerous instances of force-shaped forms found in nature (Pearson, 2006). Hence, in order to attain a harmonious and visually appealing integration in structure, designers must also take into account force shaping. An important aspect to consider is the existence of a grammatical framework that facilitates the comprehension and identification of structures contingent upon force. Force is the primary and essential element of a structure. The structure is a geometric configuration designed to transfer and distribute forces efficiently. These forces determine different materials' shape, size, and unique properties. Therefore, to fully understand a structure, it is imperative to analyze and comprehend the forces at play and how they are distributed, transmitted, and supported by various materials. Efficiently arranging and coordinating the movement of forces within a building is crucial in shaping its overall structure (Schodek, Bechthold, Griggs, Kao, & Steinberg, 2014). Hence, it is imperative to comprehend the concept of force and its constituent elements.

## VII. Forces And Their Components

In the field of architectural engineering, the term "force" is precisely defined as a vector quantity that induces the acceleration of objects. A force is defined as any influence that causes an object to change its direction or motion. When a force is applied to an object and it remains balanced, the object has the required resistance to withstand the applied forces (Ching, 1995; Muttoni, 2011).

Forces can be classified into two distinct categories: internal and external. Internal forces refer to the forces between the individual particles that constitute objects. On the other hand, external forces are exerted on objects by the surrounding environment, including gravity, lateral forces, and reactions (Allen, Zalewski, & Boston Structures Group, 2010). External forces applied to an object generate a propensity for the particles within the object to undergo movement or displacement, resulting in the emergence of internal forces. These internal forces give rise to diverse behaviors in different materials and manifest in various forms.

Mechanics, also known as the strength of materials, is the field of study that specifically examines and analyzes the behavior of particles when subjected to external forces (Muttoni, 2011; Gere & Goodno, 2012). Under conditions of equilibrium and stasis, particles cannot move in relation to one another, yet they retain a propensity for motion, generating internal forces. The propensity to undergo movement or alter its form can lead to either tangential (occurring within the same plane) or vertical (occurring perpendicular to the plane) distortions. Tangential deformations produce inter-particle forces or shear stresses, leading to the generation of shear or torsional forces (Schodek et al., 2014; Hibbeler, 2017). Conversely, vertical deformations cause normal stresses that generate axial (tensile and compressive) and bending forces.

The interaction of internal forces within particles generates internal flows within an object, resulting in bending, torsional, or shear stresses. The intricate interplay of internal forces dictates the material's ability to withstand shear, bending, or torsional stress. Nevertheless, the deformations resulting from internal forces and material behavior when subjected to load must be comprehended.

Deformation is the state that arises in objects composed of different materials due to external forces (Zuk, 1963). Under these circumstances, the interatomic bond lengths undergo alteration, and the internal forces among particles oppose the external forces, generating internal reactions that impede further deformation. If the force applied to the material is below its maximum capacity, the internal forces produced are adequate to counteract the external forces, resulting in the object remaining in a state of rest and balance. Nevertheless, if the force applied surpasses the material's limit, it results in irreversible distortion and ultimately leads to instability, failure, and the structural collapse of the object. Experimental methods (Salvadori, 1986; Gere & Goodno, 2012) precisely measure material deformation caused by forces.

The table records the ratio of stress (force applied per unit area) to strain (deformation of the object), which indicates the material's strength.

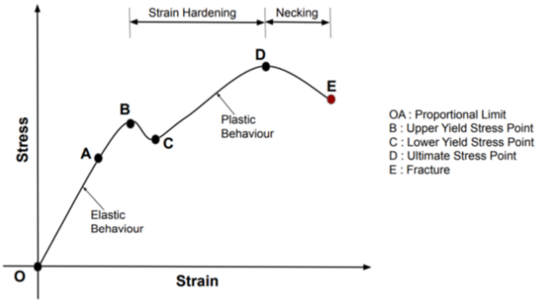

Fig 5. stress-strain relationship in materials
Source:https://www.smlease.com/entries/mechanical-design-basics/stress-strain-curve-diagram/

The condition in which an object regains its initial shape after removing a load is called elasticity (Beer, Johnston, & DeWolf, 2015). When an object experiences permanent deformation and cannot regain its original shape, this condition is called plasticity (Salvadori, 1986; Hibbeler, 2017).

When examining deformation, it is evident that objects with denser and stronger molecular bonds, like steel, diamond, and granite, are more resistant to deformations. As a result, these materials have a higher capacity to bear loads. Hence, the alteration in the shape of a substance is directly linked to its capacity to withstand external forces and its internal arrangement (Beer, Johnston, & DeWolf, 2015).

Studying nature can provide valuable insights into the effects of forces on shaping forms, enhancing our understanding of this phenomenon. Nature serves as the origin of the development of power and the creation of various structures, molded through countless years of trial and observation. Therefore, the discussion will continue by briefly analyzing the correlation between force and form in nature, as discussed by Hibbeler (2017) and Gere & Goodno (2012).

## VIII. FORCES, STRUCTURE, AND NATURAL FORMS

Architects have drawn inspiration from natural forms and structures for a considerable period of time, emphasizing functionality, economics, aesthetics, and durability. These forms have experienced evolutionary processes over millions of years, influenced by environmental factors to meet different requirements. Crucial elements in this process involve the ability to endure, withstand, and withstand external influences such as gravity, wind, seismic activity, and temperature changes (Benjamin, 1990). Over centuries, natural forces have shaped these structures, removing vulnerabilities and adjusting them to fit specific spatial and temporal conditions, all while meeting functional, economic, and other natural needs (Salvadori, 1986).

Whether natural or synthetic, materials undergo deformation when external forces are applied to them, and the extent of deformation differs among various materials. Wood exhibits greater deformation than steel under a constant load, reducing load-bearing capacity. Natural and artificial materials exhibit distinct variations in their reactions to environmental forces. These forces influence the internal arrangement of particles in natural materials, which affect their load-bearing capacity based on spatial and temporal conditions (Allen, Zalewski, & Boston Structures Group, 2010).

As an illustration, a child's skeletal structure and fragile internal organs undergo maturation and fortification over time due to growth and engagement with the surrounding environment. Under severe circumstances, such as physical trauma or bone breakage, the human body can undergo repair and fortification. The ability to regenerate sets living natural forms apart from inanimate or synthetic materials, which have consistent and predictable load-bearing capacities. Another significant distinction lies in how these materials support weight and the transmission of forces within them. Materials that have gathered and undergone compression typically demonstrate increased compressive strength, whereas those formed under tension exhibit higher tensile strength (Schodek et al., 2014; Gere & Goodno, 2012).

Natural materials lack the uniformity and isotropic properties commonly found in industrial materials such as steel, which have consistent mechanical properties in all directions (Hibbeler, 2017). Natural materials, consisting of proteins, sugars, calcium, and organic compounds, generally exhibit inferior strength compared to synthetic materials such as metals, which possess dense, geometric, and sturdy atomic structures. Nevertheless, this does not indicate any deficiency in the ability of natural structures to bear weight. Natural structures have developed over millions of years to effectively withstand and support heavy loads by interacting with environmental forces (Beer, Johnston, & DeWolf, 2015).

Living organisms that can grow in response to external forces undergo a transformation of internal force levels, forming layered structures. This implies that the stratified load-bearing flows influence the structure of the form, molding the particles as they grow and producing force levels that represent the combined effect of these forces. Therefore, if forces can freely circulate within the structure, it will inherently support loads optimally. The quantity and thickness of the material at each location are directly related to the forces it must withstand, resulting in an ideal load-bearing structure (Muttoni, 2011).

As an illustration, the human skeletal system, which consists of roughly equal amounts of protein and mineral substances, serves the dual purpose of supporting body weight and safeguarding internal organs such as the heart and lungs. Additionally, it enables movement and accounts for approximately 15% of the total body weight. Bone exhibits a compressive strength similar to cast iron, but its lighter weight can be attributed to its porous structure. Bone has a specific gravity of approximately 1.75 $g/cm^3$, an ultimate compressive strength of around 2050 $kg/cm^2$, and an ultimate tensile strength of about 1350 $kg/cm^2$. On the other hand, cast iron has a specific gravity of 7.87 grams per cubic centimeter, and its ultimate tensile and compressive strengths are approximately 2000 $kg/cm^2$. The lightweight nature of bone in relation to its considerable strength is attributed to its porous structure, composed of small plate-like particles arranged in a three-dimensional, force-responsive manner. The image below depicts the systematic alignment of bone particles when subjected to compressive and tensile forces, specifically illustrating the stress-induced structure of the femur bone (Timoshenko, 1953).

The marked lines represent the arrangement of internal bone particles under compression and tension, also known as isostatic lines. These particles undergo growth and adaptation to withstand applied forces, a process impossible with synthetic materials. Isostatic lines, representing tensile and compressive forces, can be found in synthetic materials. However, the arrangement of particles in these materials is predetermined and unchangeable. Therefore, analyzing how forces are distributed within these materials (Gere & Goodno, 2012; Hibbeler, 2017) is important.

## IX. FORCES, STRUCTURE, AND ARTIFICIAL FORMS (ARCHITECTURAL FORMS)

Generally, the term "form" has distinct practical implications in different scientific and intellectual domains. The term "form" can be understood as shape, appearance, manner, configuration, structure, state, the composition of elements that create a unified whole, and character, nature, and structure. In this study, the term "form" pertains to the observable structure and organization of components, as Herbert Read defines it as the visual characteristic of an object (Read, 1994). Hence, form embodies an object's observable nature and distinctiveness, enabling its recognition and differentiation.

Architectural form refers to the tangible representation of matter that gives it shape, including its constituent elements, proportions, and dimensions (Hoshyar & Barough, 2013). It represents and communicates significance and is connected to human cognition of the surroundings, shaped by human comprehension of the world (Giedion, 1948). Form is an essential element of architecture and must align with multiple influential factors, including value systems, cultures, environmental conditions, functionality, and sustainability. Throughout history, numerous architects have deemed it to be the utmost crucial element in design, frequently eclipsing other considerations. Considering the significant impact of economic conditions on human societies, any approach must establish favorable living conditions for humans by enhancing all aspects that influence architecture, including economic factors.

Throughout history, humans have consistently drawn inspiration from natural forms, which they replicated in their early architectural endeavors. For centuries, buildings were characterized by thick bases and arched, heavy roofs made of clay, brick, and stone. The load-bearing mechanisms in these structures imitated natural patterns, incorporating compressive and tensile forces. They utilized thick, heavy elements that could endure substantial gravitational and lateral forces without structural failure.

The emergence of the Industrial Revolution and the enhanced manufacturing of construction materials such as iron, steel, and concrete, coupled with progress in the timber industry, led to substantial changes in building structures. Designers and builders gained access to new construction possibilities, including tall buildings, horizontal planes, slender bases, innovative forms, and advanced construction techniques (Salvadori, 1986). This transformation altered the characteristics of materials, making the natural load-bearing principles more complex (such as layered load transfer) and introducing additional factors to consider for shear, bending, and torsional forces in these novel materials and structures.

Modern materials possess distinct, dense configurations, predominantly manufactured through industrial procedures that entail the application of heat and the amalgamation of various elements. Consequently, their behavior when subjected to external forces is intricate yet quantifiable and documentable (Ching, 2014). The resistance curves of materials like steel illustrate their deformation characteristics when subjected to external forces, indicating a controlled and uniform response with a substantial ability to bear loads (Beer et al., 2015).

The load-bearing capacity of each of these materials leads to varying thicknesses in load-bearing components. Therefore, materials with greater resistance to external forces necessitate smaller thickness and surface area dimensions than other materials. According to Beer et al. (2015), as the amount of alloy in iron increases, its ability to bear loads also increases.

Acknowledging that every material bears loads according to its intrinsic properties is crucial. Therefore, certain materials may demonstrate higher tensile strength, while others may have greater resistance to compression, or some may have equal capacities for both tensile and compressive forces (Ching, 2014). The equivalent tensile and compressive strength in materials gives rise to a notable characteristic that will be thoroughly examined.

The coexistence of tensile and compressive forces within a section requires the existence of a region or surface where neither tension nor compression is present. The neutral axis, also called the center of the object's surface, aligns with the surface of elastic bodies (Gere & Goodno, 2012). Put simply, the neutral axis serves as the boundary that links the sections of a structural member that experience tension and compression. The geometric properties of the section, including its shape, area, width, and height, have a substantial impact on the bending capacity of the section (Beer et al., 2015).

The morphology of the section reflects the spatial arrangement of particles within the cross-sectional area of the material. When subjected to bending forces, these particles experience both tensile and compressive reactions (Hibbeler, 2017). The combined tensile and compressive forces are evenly distributed on both sides of the neutral axis. Therefore, the external load is transformed into an internal moment of reaction forces, which are determined by the section's shape, area, and dimensions (Popov, 1990).

When a structural element is subjected to a load, it bends, and the cross-section rotates and changes its angle around the neutral axis, as shown. Hence, the bending force is directly linked to the rotational properties of the cross-sectional area of the structural element. The term used to describe this characteristic is the moment of inertia. The moment of inertia measures an element's resistance to bending forces, calculated as the second moment of area of its cross-section relative to the neutral axis (Gere & Goodno, 2012).

The rotation of the cross-section of a structural element due to bending stress is determined by the section's integrity. Sectional integrity refers to the state in which all components and parts of a section are securely joined and harmonized. When the layers of a section are separated, the bending force will cause the layers to function independently, sliding over each other. The load-bearing will only happen through the bottom layer of the assembly (Gere & Goodno, 2012). The absence of integrity and adhesion between layers leads to a decrease in the load-bearing capacity of multiple stacked layers, equivalent to that of a single layer. On the other hand, when the layers are strongly bonded to each other, minor reactions happen at the boundary between the layers, which allows them to bear the load as a whole. The term used to describe these reactions is shear forces (Hibbeler, 2017).

Shear forces maintain a section's structural integrity by enabling it to withstand tension and compression, which in turn helps it resist bending and increase its bending capacity (Popov, 1990).

When the bending forces (shear forces) in a cross-section cause the reactions to surpass the structural element's capacity to withstand, the adhesion between the layers and particles composing the element breaks down. As a result, the section becomes compromised and weak, ultimately resulting in a collapse of the structure (Hibbeler, 2017). This illustrates that the flexural strength of various materials differs based on their composition, structure, and adhesive properties between particles, which subsequently affect the materials' ability to withstand shear forces. Wood typically exhibits a lower capacity to bear loads than steel or steel fibers (Gere & Goodno, 2012).

The resistance to tensile and compressive forces, which is a critical factor in bending capacity, is significantly influenced by the type of material (Popov, 1990). Hence, the bending capacity of a structural element is predominantly determined by the magnitude of the applied bending force, the span of the load-bearing element, and its connection interface with other elements and the ground. Additionally, the constituent particles' load-bearing capacity and the structural member's material properties, such as wood or steel, play a significant role (Gordon, 2003).

The bending capacity of a member is primarily determined by its geometry and rotational properties. By modifying and increasing the moment of inertia of the cross-section, the internal reactions can be appropriately distributed and reduced, ensuring that they remain within the acceptable limits of the chosen material (Beer et al., 2014). According to Hibbeler (2017), the bending force applied is directly proportional to the load magnitude raised to the power of one and the span length raised to the power of two. Therefore, to effectively reduce the bending force, it is more effective to control and decrease the span length of the load-bearing member rather than simply decreasing the load.

Furthermore, when considering the moment of inertia relationship, which measures the ability of a structural member to resist bending, the width of the section has a significantly smaller impact compared to its depth. Thus, the load-bearing capacity can be managed and improved by augmenting the depth of the structural member's section and diminishing its span. This method guarantees that the structural member's cross-sections are shaped to match the predetermined capacity of the materials used. As a result, it determines the structural form and accomplishes the structural design (Gordon, 2003).

Structural design efficiently and effectively utilizes materials to ensure that a structure can safely and dependably withstand and transmit all possible forces exerted on it, while securely transferring them to the ground. Considering the impact of depth and span on the ability to bend and bear loads, it is clear that if the span and material of a structural component remain the same, changing its depth can greatly improve its load-bearing capacity (Gere & Goodno, 2012; Popov, 1990).

It is important to emphasize that structural design extends beyond individual structural components and includes the entire structural system. This incorporates beams, columns, walls, roofs, floors, and foundations (Salvadori, 1986). Therefore, various structural systems such as frames, trusses, space trusses, shells, and membranes are created (Ching, 1995).

Structural engineering involves integrating these components to create a unified system capable of efficiently supporting and transmitting loads. Frames serve as the structural framework for various constructions, effectively distributing loads using interconnected beams and columns (Ambrose & Tripeny, 2011). Trusses, commonly employed in constructing roofs and bridges, use triangular components to effectively manage tension and compression forces (Engel, 1981). Space trusses expand upon this concept in three dimensions, enabling the construction of expansive, unobstructed areas without the need for internal support (Schodek, Bechthold, Griggs, Kao, & Steinberg, 2014).

Shell structures, renowned for their slender and curved shapes, evenly distribute forces over their surfaces, resulting in visual appeal and practical advantages (Gordon, 2003). Membrane structures of pliable materials depend on tension to preserve their forms and are commonly employed in contemporary tensile architecture (Harris & Piersol, 2002).

Hence, the successful creation and execution of these systems necessitate thoroughly comprehending the interplay between each constituent within the overarching framework. This comprehensive approach guarantees that the building fulfills functional prerequisites and satisfies safety and stability criteria (Gere & Goodno, 2012).

Table 2. Historical development and formation of structural engineering

| **Material** | **Specific Gravity (g/cm$^3$)** | **Ultimate Compressive Strength (kg/cm$^2$)** | **Ultimate Tensile Strength (kg/cm$^2$)** | **Typical Uses** |
|---|---|---|---|---|
| Bone | 1.75 | 2050 | 1350 | Human skeletal support, prosthetics |
| Cast Iron | 7.87 | 2000 | 2000 | Machinery, pipes, automotive parts |
| Steel | 7.85 | 4000 | 2500 | Buildings, bridges, infrastructure |
| Concrete | 2.4 | 2000 | 150 | Foundations, structures, pavements |
| Timber | 0.6 - 0.9 | 500 - 900 | 80 - 100 | Residential buildings, furniture |
| Aluminum | 2.7 | 400 - 500 | 300 - 400 | Aircraft, automotive, construction |

Sources: Timoshenko (1953), Beer et al. (2015)

## X. Results

The relationship between structural forces and architectural forms was investigated by analyzing historical and contemporary texts, specific architectural examples, natural forms, structural models, diagrams, and scholarly articles. The findings thoroughly comprehend how structure impacts architectural form and the inherent correlation between the two fields.

### Historical and modern texts

Examining both past and present texts has revealed a consistent progression in understanding and implementing structural principles in architecture. Classical texts established fundamental theories, whereas modern texts focused on innovative methodologies and the incorporation of cutting-edge materials. This sequence emphasizes the significance of comprehending historical contexts to guide present architectural practices and design strategies.

Distinct Architectural Examples

Notable architectural works were used as case studies to demonstrate the practical implementation of structural principles. Notable endeavors like the Eiffel Tower, Sydney Opera House, and contemporary skyscrapers are prime examples of how structural factors greatly impact the overall design. These examples emphasize the essentiality of architects closely cooperating with structural engineers to accomplish both aesthetic and functional goals.

Natural Forms and Structural Efficiencies

Examinations of organic shapes, such as bones, shells, and plant structures, have shown that nature effectively supports weight by strategically organizing materials. For example, the porous structure of the human femur offers both strength and lightweight characteristics, which can be used as a model for designing efficient architectural shapes. These natural instances highlight the capacity for biomimicry in architectural design, wherein natural efficiencies can be replicated in man-made structures.

Structural models, diagrams, and simulations

Structural models, diagrams, and computer simulations were employed to thoroughly analyze the behavior of forces in different forms and materials. These tools enabled the visualization of load distribution and deformation under various conditions, offering valuable insights for optimizing structural designs. The simulations emphasized the significance of considering force distribution and material characteristics during the design phase to attain efficient and resilient structures.

Academic Articles and Periodicals

The scholarly articles and journals reviewed showcased the most recent advancements and theoretical progressions in structural engineering and architecture. Peer-reviewed studies offer empirically supported insights into the behavior of materials and the efficacy of various structural systems. This academic viewpoint emphasized the importance of incorporating scientific research into architectural practice, guaranteeing that design choices are based on strong structural principles.

Main Discoveries

Incorporating Structural Principles into Design: The study confirmed that architects must possess a profound comprehension of structural principles. This integration results in novel and effective designs that harmoniously balance aesthetics and functionality.

The significance of collaboration: The effectiveness of collaboration between architects and structural engineers is crucial. The case studies illustrated that successful projects frequently arise from interdisciplinary collaboration, wherein the expertise of each professional is utilized to its fullest extent.

Biomimicry in Architecture: Utilizing materials and structural forms inspired by nature provides valuable insights for architectural design. By replicating natural structures, architects can achieve sustainability and resilience in buildings.

The advancement of materials and technologies has broadened the potential for architectural designs. Technological advancements, such as high-strength concrete, advanced composites, and 3D printing, enable the construction of intricate and highly efficient structures.

Educational Frameworks: All-encompassing educational frameworks that incorporate structural knowledge into architectural curricula are required. This program will provide future architects with the essential skills to grasp and implement structural concepts comprehensively and proficiently.

## XI. DISCUSSION

Although buildings have existed for thousands of years, with a primary emphasis on stability and longevity, the field of structural engineering, which involves analyzing forces and ensuring the strength of buildings, has only been around for less than 300 years. Form development has always been influenced by factors such as functionality, aesthetics, and economic considerations. However, structural forces also mold the form to establish a strong, long-lasting structure. The emergence and formation of natural forms clearly demonstrate the combined impact of functionality, aesthetics, economic considerations, stability, and longevity.

Natural forms arise from a gradual evolution and interaction with environmental forces, resulting in shapes crafted with minimal materials. Their structures are layered, with load flow occurring in tension and compression. Modern buildings, in contrast, are constructed using materials that are the outcome of sophisticated technology and intricate manufacturing procedures, engineered to possess specific physical characteristics and precise load-bearing capabilities. The load distribution in these materials is no longer limited to tension and compression alone. These materials' remarkable shear and bending resistance have facilitated the construction of skyscrapers and large-span roofs. The inherent industrial properties of these materials enable them to possess both tensile and compressive capabilities, setting them apart from organic or natural materials as well as traditional materials such as stone and clay that were utilized in previous times.

The ability of these materials to withstand both tension and compression simultaneously allows them to support bending forces. This feature enables the construction of expansive horizontal spans and towering structures, in contrast to the formations found in nature. Bending is affected by multiple factors, with the moment of inertia being a critical parameter. The moment of inertia, a measure of an object's resistance to rotational motion, is influenced by the dimensions of the load-bearing element's cross-section, specifically its depth and width. This attribute renders it an essential instrument in design, ultimately creating diverse structural systems.

## XII. CONCLUSION

Contemplating the connection between structure and architecture is an essential topic that enables the practical use of structural understanding in the design context. Structure refers to the arrangement and control of forces, whereas form is the outcome of the interplay between internal and external forces. These interactions result in the creation of sizes, thicknesses, and shapes of structural elements made of different materials, which are influenced by different force systems. Bending, also known as flexure, is a crucial and substantial force among these forces. While natural forces typically exhibit a layered flow, bending is the dominant factor in shaping artificial materials and architectural structures.

The ability of a section to withstand bending is directly influenced by the magnitude of the applied loads, the reactions at the supports, the length of the member, the properties of the section, and the characteristics of the material. Modifying any of these variables will modify the section's load-bearing capacity. Thus, by manipulating each of these factors, the ability of a structural element to support weight can be adjusted, thereby forming the basis of structural design.

In addition, it is possible to design individual members and a combination of members to create a three-dimensional load-bearing system within a building. In intricate amalgamations, these individuals form diverse load-bearing structures that result in various architectural designs. This demonstrates the ability to enhance design options, illustrating how the structure, by its shape, impacts architectural form. As a result, architecture, influenced by structure, not only becomes secure but also assumes its form.

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