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A REVIEW: 7000 YEARS OF BUILDING STRUCTURES

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ABSTRACT

The purpose of this review article is to examine the changes and developments in structural systems and materials up to the present day through a holistic perspective, considering the societal dynamics of each period. The article includes a literature review and investigates the development of structures through the concepts of "structural system," "construction material," and "structural innovation." In selecting the structures discussed in the article, care has been taken to include those that pioneered new structure types, and/or materials for subsequent structures. The study covers an approximately 7,000-year period from the Neolithic era to the present. Therefore, within this broad time frame, the article provides brief/concise information on the concepts of "structural system," "construction material," and "structural innovation" about the examined structures. In the study, it is observed that until the Industrial Revolution, building construction was carried out using traditional materials and construction techniques. Moreover, faith was a major motivation in pushing the boundaries of construction techniques under the conditions of the time. This motivation changed with the Enlightenment era, as the new thought process resulting from the Industrial Revolution replaced the motivation of "faith" with "building for society" through new technological possibilities. New forms of society brought with them new construction technologies and typologies. This situation persisted until the late 20th century, but it changed with the use of computer technology in design and construction phases. Since then, structural concerns, which had been a significant constraint in building construction, have become less of a priority for designers. From this point of view, the article is structured as follows after the "Introduction" section: "Building for Faith: The Limits of Traditional Materials," "The Machine Age: Building in the Light of Modern Science and Engineering," and "Free from Structural Constraints: The Impact of Computers." In the conclusion, examples are listed according to the concepts of "structural system," "construction material," and "structural innovation," thereby presenting the results of the study.

Keywords: Structural Systems, Building Materials, Traditional Construction Systems, Industrial Revolution, Computer Age.

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YAPI STRÜKTÜRLERİNİN 7000 YILI ÜZERİNE İNCELEME

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ÖZET

Bu derleme makalesinin amacı, günümüze kadar olan sürede yapı strüktürlerinin ve strüktür malzemelerinin değişimini ve gelişimini döneminin toplumsal dinamikleriyle birlikte bütüncül bir bakışla incelemek ve strüktürlerin geçmişten günümüze gelişimini bu gelişime etkisi olan etmenlerle birlikte ortaya koymaktır. Makalede literatür araştırması gerçekleştirilmiş; strüktürlerin gelişimi "strüktür türü", "strüktür malzemesi" ve "strüktürel yenilik" kavramları üzerinden incelenmiştir. Makale kapsamında ele alınan yapıların seçiminde kendinden sonra gelecek yapılar için öncü rol oynayan yeni bir yapı tipolojisinin, strüktür türünün ve/veya strüktür malzemesinin öncüsü olan yapıların seçilmesine dikkat edilmiştir. Çalışma neolitik dönemden günümüze yaklaşık 7000 yıllık bir dönemi kapsamaktadır. Bu sebeple, bu geniş zaman aralığında gerçekleştirilen bu çalışmada ele alınan yapılarda "strüktür türü", "strüktür malzemesi" ve "strüktürel yenilik" kavramlarına ilişkin kısa/öz bilgiler sunulmuştur. Araştırmada, endüstri devrimine kadar olan sürede yapı üretiminin geleneksel malzemeler ve geleneksel yapım sistemleri ile gerçekleştirildiği bununla beraber, inancın dönemin koşullarında yapım tekniklerinin sınırlarının zorlanmasında başlıca motivasyon kaynağı olduğu görülmüştür. Bu motivasyon aydınlanma çağı ile değişmiş, yeni düşünce biçiminin bir sonucu olan endüstri devriminin sağladığı yeni teknolojik olanaklarla "inanç" motivasyonunun yerini "toplum için inşa etmek" almıştır. Yeni toplum biçimleri yeni yapım teknolojilerini ve tipolojilerini de beraberinde getirmiştir. 20. Yy'nin ikinci yarısına kadar süren bu durum bilgisayar teknolojilerinin yapı üretiminde etkin olarak kullanılmasıyla değişmiş, bu dönemden sonra yapı üretiminde bu güne kadar önemli bir kısıt olan strüktürel kaygılar yapı tasarımcıları için öncelikli olmaktan çıkmıştır. Bu noktalardan hareketle makale, "giriş" bölümünden sonra "inanç için inşa etmek: doğal malzemelerin sınırları", "makine çağı: modern bilim ve mühendisliğin ışığında kentler" ve "strüktürel kısıtlardan uzak: bilgisayarın getirdikleri" başlıkları altında yapılandırılmıştır. Makalenin son bölümü olan sonuç bölümünde ele alınan örnekler yine "strüktür türü", "strüktür malzemesi" ve "strüktürel yenilik" kavramları ekseninde görselleştirilerek, çalışmanın sonuçları ortaya koyulmuştur.

Anahtar Kelimeler: Yapı strüktürleri, Yapı malzemesi, Geleneksel yapım sistemleri, Endüstri devrimi, Bilgisayar çağı.

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1. INTRODUCTION

With the emergence of built environments, structural systems began to form and have developed and diversified through social changes and transformations. This review article aims to examine the changes and developments in structural systems over the past 7000 years from a holistic perspective, along with the social, cultural, and technological dynamics of each period.

By conducting a literature review, the development of structural systems has been analyzed around three main concepts: "structural system," "construction material," and "structural innovation." In the article, example structures from each period were selected. In selecting example structures, care was taken to choose those that played a pioneering role in introducing new types of structural types, and/or construction materials for ensuing buildings. Because the research covers a long period, only brief details about "structural system," "construction material," and "structural innovation" are provided for the example structures.

The sources used in the literature review include academic books, articles, and reports that address the architectural and structural changes and developments from various perspectives. Some of these works that examine this development historically within the dynamics of their periods are as follows:

• The Story of Architecture (Patrick Nuttgens, 1983): Examines architectural development from ancient times to the end of the 20th century through examples of buildings.

• Structure and Architecture (Angus J. Macdonald, 1994): The main theme of this work is the relationship between structural design and architectural design.

• The Story of Architecture of the 20th Century (Jürgen Tietz, 1999): Provides a comprehensive view to understand the historical and cultural contexts of building production in the 20th century and addresses the social and cultural influences on architectural history.

• A World History of Architecture (Marian Moffett, Michael Fazio & Lawrence Wodehouse, 2004): Investigates architectural products from prehistoric times to the end of the 20th century worldwide, considering geographical locations and social dynamics, using example structures.

• Architecture Atlas (Atlas Baukunst) (Werner Müller & Gunther Vogel, 2005): Composed of general overview and architectural history sections, this work examines the history of architecture and building structures up to the present day.

• Understanding Architecture: Its Elements, History, and Meaning (Leland M. Roth and Amanda C. Roth Clark, 2014): The book is divided into two sections. The first section deals with the elements of architecture, while the second section covers the historical development of structural systems within the broad scope of architectural history. It also examines architectural periods and some innovative structures from those periods.

• The Story of Architecture (Witold Rybczynski, 2022): Rybczynski selects several buildings from each period and examines the production of these buildings considering their commissioning, construction, and usage conditions.

Additionally, within the scope of this study, books, academic articles, and reviews specific to certain structures and/or periods constitute other sources. Existing studies address the development of buildings from the broad perspectives of architectural history and design. This study, however, aims to examine this development specifically in terms of building structures, utilizing these sources. All sources examined and included in the article are listed in the references section.

As a result of the literature review, the article is structured into three main sections following the introduction:

• "Building for Faith: The Limits of Traditional Materials": This section examines the construction materials, structural systems, building techniques, and structural innovations used in the period, highlighting the role of faith and religious motivations in the development of structural systems.

• "Machine Age: Building in the Light of Modern Science and Engineering": Under this heading, the evolution of buildings during the Industrial Revolution and modern engineering is explored, including new construction materials, construction techniques, and structural innovations.

• "Free From Structural Constraints: The Impact of Computers": This section addresses the new opportunities provided by computer technology in building design and its effects on construction practices.

In the conclusion of the article, the structures and periods discussed are summarized in a table based on the concepts of "structural system," "construction material," and "structural innovation," presenting the findings of the study.

This review article aims to evaluate the development of structural systems over a broad period through a holistic approach, focusing on the socio-cultural, scientific, and technological innovations of each period. As mentioned before, due to the wide time range covered by the study, only brief information about the concepts defined by the study is provided for the structures discussed. Additionally, some structures have been excluded from the scope of the study. Detailed research conducted over a narrower time frame will form the basis for future studies.

2. BUILDING FOR FAITH: THE LIMITS OF TRADITIONAL MATERIALS

Built environments have been created for various purposes. Initially, the primary aim was protection from environmental conditions. However, starting from the Palaeolithic period, humans began to integrate natural phenomena like rain and thunder, as well as animals vital to their survival, into their belief systems. This integration led to the organization of ceremonies and rituals. With the onset of the Neolithic period, belief systems further evolved, eventually leading to the construction of ritual spaces known as cultic buildings (Kolaric, Çatalhöyük, 2014).

During the Neolithic period, cultic buildings were sometimes constructed separately from settlement areas and sometimes integrated into residential units. One of the significant Neolithic settlement sites is Çatalhöyük (Figure 1). The reconstruction of a cultic building in Çatalhöyük can be seen in Figure 2.

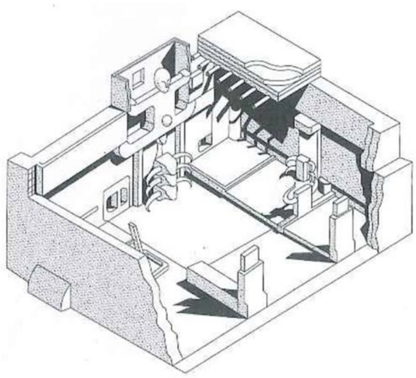

Figure 1. Reconstruction of Çatalhöyük (Kolaric, Çatalhöyük, 2014).
Figure 2. The reconstruction of a cult unit at Çatalhöyük, dating back to approximately 6500–5700 BCE (Moffett, Fazio, & Wodehouse, 2004).

This evolution highlights how built environments not only served practical purposes such as protection but also became integral to spiritual and communal practices.

The influential role of faith in the production of structures continued from the Neolithic period into the early advanced civilizations. In these civilizations, while civil architectural products were built parallel to the development of civilization, structures that pushed the boundaries of existing building techniques and became masterpieces of their time were often religious buildings. In other words, the most innovative structures were built for faith.

The Sumerians, one of the earliest known civilizations, existed between approximately 3200 BC and 300 AD. Sumerians were ruled by priest-kings. Considering the built environments created by the Sumerians, it is obvious that the structures where the art and techniques of construction were most effectively utilized were the "ziggurats". Ziggurats are temple towers consisting of multiple terraced levels connected by ramps with a temple constructed on top. One of the well-preserved monumental temples/ziggurat is the Ur Ziggurat, located in the city of Ur (Figure 3). The core of the ziggurat was constructed using sun-dried bricks and coated with bitumen to protect it from external weather conditions (Müller & Vogel, 2005).

Figure 3. Ur Ziggurat, Mesopotamia-Iraq, circa 2100 BCE (Moffett, Fazio, & Wodehouse, 2004).

During the same period (circa 3100 BC to 300 AD), in a different geographical region, the civilization of Ancient Egypt thrived with a similarly structured social life based on religious authority. In Egypt, too, the influence of belief on construction techniques is vividly seen in the existence of the Egyptian Pyramids. The first pyramid known to us today is the Step Pyramid of Djoser (Figure 4).

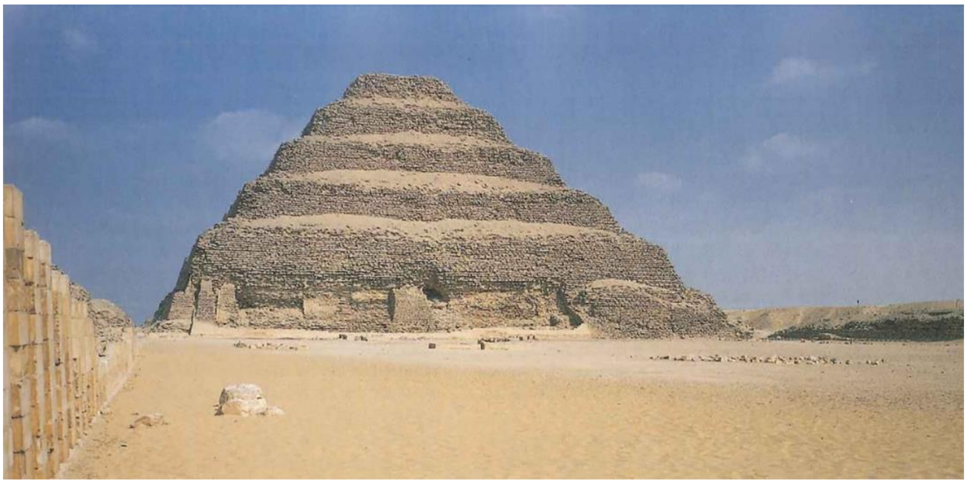

Figure 4. Step pyramid of Djoser, Saqqara-Egypt, around 2630 BCE (Moffett, Fazio, & Wodehouse, 2004).

The funerary structure was commissioned by Pharaoh Djoser and, marks a significant innovation in ancient Egyptian architecture. This pyramid, which symbolizes the transition of pharaohs from humanity to divine life, was constructed by stacking smaller rectangular mastabas (which were earlier flat-roofed, rectangular tombs) on top of one another.

Unlike previous constructions using mud bricks, reeds, and wooden poles, the Step Pyramid was built primarily using limestone. The use of stone as a building material aimed to ensure the permanence of the structure, reflecting the belief in an afterlife. This innovation served as a turning point for the construction of future religious buildings in Egypt and beyond (Roth & Clark, 2014).

The Temple of Amun at Karnak, another significant religious structure where stone was used extensively as a building material, exemplifies the importance of temple construction in Ancient Egypt. One notable feature of this temple is the Hypostyle Hall, a hall with a roof supported by columns, showcasing one of the earliest applications of the column-beam system using stone (Figure 5).

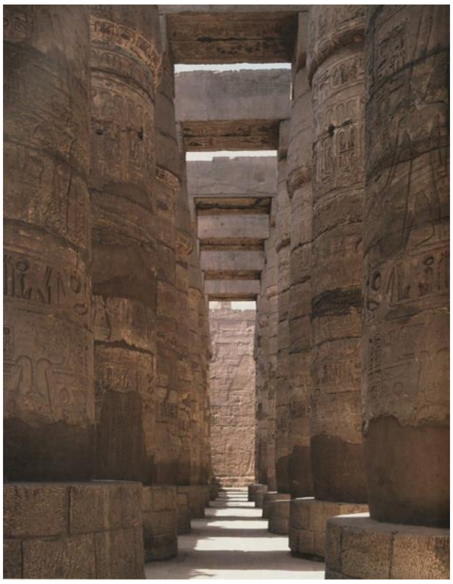

Figure 5. Hypostyle Hall of the Temples of Amun-Ra and Khonsu, Karnak, Egypt, 1529–1156 BCE (McCarter & Pallasmaa, 2012).

The Hypostyle Hall at Karnak measures 97.5 m x 48.75 m and contains 134 stone columns (Figure 6). The 12 columns positioned along the central axis of the hall are standing at a height of 21 m with a diameter of 3.6 m. Surrounding these central columns are an additional 122 columns, slightly smaller at 12.8 m in height and 2.75 m in width. The configuration of these columns was strategically planned to allow natural light to enter the hall from the ceiling (Roth & Clark, 2014).

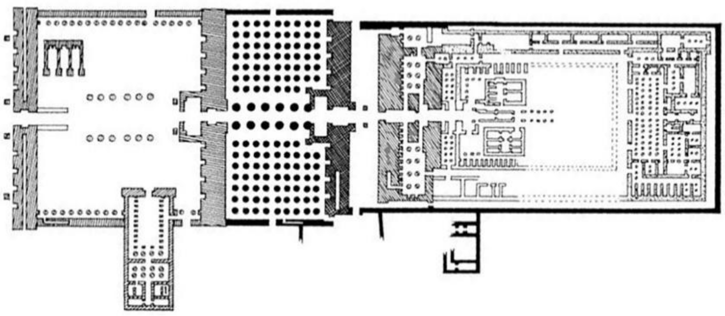

Figure 6. Plan of the Temple of Amun, Karnak, Egypt, 2000-323 BCE, and the Hypostyle Hall constructed by Ramses II, 1315–1235 BCE (Roth & Clark, 2014).

This deliberate architectural plan not only highlights the structural capabilities of using stone but also demonstrates the sophisticated planning and engineering prowess of the Ancient Egyptians in creating monumental religious spaces.

Religious structures often utilize durable materials like stone due to their perceived permanence and symbolic significance. On the other hand, secular buildings, which were typically administrative or residential, employed more practical and less enduring materials like mud bricks reinforced with straw. The application of hard plaster on these mud brick surfaces helped to protect and stabilize the structure. Thus, the choice of construction materials and techniques reflected the societal values and intended functions of the buildings during that period.

Social and cultural developments of ancient Egyptian civilization expanded through trade routes to Lebanon and also Mesopotamia. The influence of these advanced cultures also reached the southern coasts of Anatolia and extended from Anatolia to the Aegean, contributing to the emergence of Europe's earliest advanced civilizations. This cultural exchange is exemplified in Greek civilization, where the initially simple temples, originally built around the 8th century BCE to house sacred statues, evolved under the influence of Egyptian culture to incorporate stone construction, departing from earlier adobe walls, wooden columns or pillars, and thatched roofs (Moffett, Fazio, & Wodehouse, 2004). During the Classical period of Greek architecture, the development of public life and the emergence of the concept of democracy led to the construction of various public buildings such as bouleuterions, stoas, gymnasiums, theatres, and more. However, despite the diversity of public structures, temples continued to be the architectural types that defined structural boundaries.

One of the most significant Greek temples that has survived to the present day is the Parthenon Temple, located within Athens, constructed around 437–438 BCE (Figure 7). Built using stone and marble, the temple measures approximately 69.5 m x 30.9 m in plan dimensions. It features over 48 marble columns, each standing over 10 m high. These columns support a roof made of wooden beams covered with tiles (Borden, et al., 2008).

Figure 7. Parthenon Temple (author).

The construction of the Parthenon employed a dry stone walling technique known as "anastylosis," where stone blocks were stacked directly on top of one another without any mortar or leveling material. In Greek architecture, especially in earthquake-prone regions, precautions were taken when using dry stone walling, often incorporating metal clamps or dowels to reinforce the structure (Roth, 2000).

During the period when Greek architecture flourished on the Greek mainland and the western coast of Anatolia, the Roman civilization emerged on the Italian Peninsula around the 8th century BCE. Romans revolutionized architecture significantly, both in terms of materials and architectural elements. They invented the arch, vault, groin vault, and dome; utilizing concrete to construct these circular forms with unprecedented span lengths. This innovation enabled them to create numerous structures that weren't previously achievable in construction (Macdonald, 2001).

Among all these architectural innovations, the Pantheon Temple (built between 118–128 BCE) stands out from other structures due to its exceptionally wide dome, which is the largest constructed up to that time. Dedicated to all gods, the temple's dome has a diameter of 43.4 m. As the dome rises, the density of its material decreases, and at the highest point of the dome, there is a 9.1 m diameter opening called the oculus (Figure 8) (Nuttgens, 1983; Mark & Hutchinson, 1986; Roth & Clark, 2014).

Figure 8. Pantheon, view of the interior (author).

The distance from the top of the dome to the floor is equal to the dome's diameter. In other words, a perfect sphere can be drawn under the dome. The concrete of the dome exerts a significant downward force. This load is transferred through 8 barrel vaults to the ground (Figure 9) (Mark & Hutchinson, 1986).

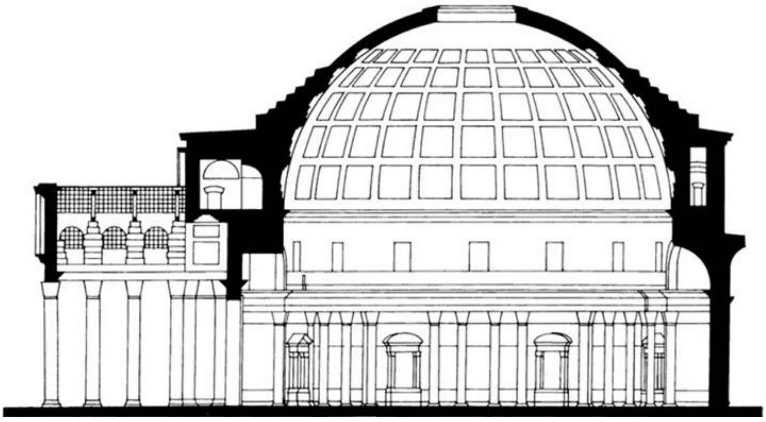

Figure 9. Section of the Pantheon, Rome, Italy, 118–28 BCE (Roth & Clark, 2014).

After the division of the Roman Empire and the official adoption of Christianity as the state religion in the Eastern Roman Empire (Byzantine Empire), churches were initially converted from Roman basilicas to serve as public places of worship. Over time, a large number of churches were constructed. With the completion of its roof structure in the 6th century AD, Hagia Sophia Church (Figure 10) once again pushed the limits of spanning lengths using the masonry construction technique.

Figure 10. View of Hagia Sophia Church (McCarter & Pallasmaa, 2012).

The roof system of Hagia Sophia consists of a central dome supported by two half-domes in two directions. This roof system gave rise to a new architectural element that made the dome-half dome relationship possible: the triangular spherical “pendentive”. In Figure 11, the plan of Hagia Sophia Church can be seen, while Figure 12 shows the section of Hagia Sophia Church.

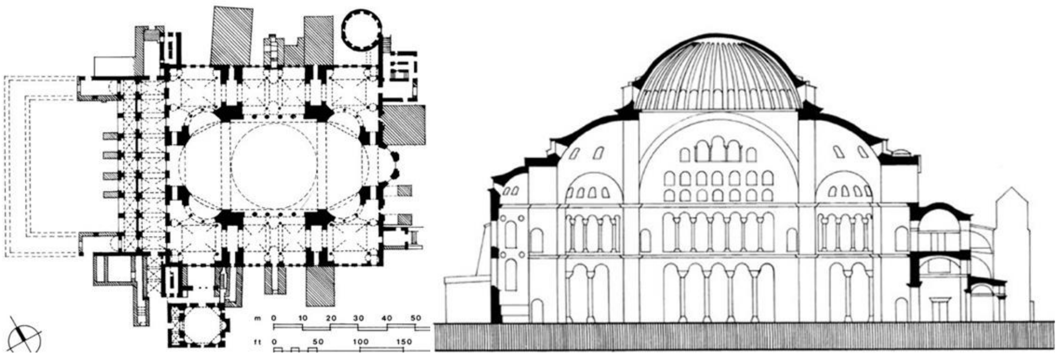

Figure 11. Plan of the Hagia Sophia Church (left) (Roth & Clark, 2014).
Figure 12. Cross-section of the Hagia Sophia Church (right) (Roth & Clark, 2014).

After the fall of the Western Roman Empire in the 5th century AD due to the migration of tribes, Europe entered a dark period dominated by chaos. The struggle between cities led to the development of fortified cities and city walls as a defense strategy. In the 10th to 13th centuries, as a result of scholastic thought and the medieval monks' dedication to withdrawing from secular affairs, numerous monasteries with thick masonry walls and stone arches were constructed. These monasteries were not only used as places of worship but also became political, cultural, and agricultural centers of their regions. The Abbey of Saint Martin in France (1001–1026) is an exemplary representation of these medieval monasteries (Figure 13) (Roth, 2000).

Figure 13. View of the Monastery of Saint Martin (Janberg, 2022).

In the 12th century, with the desire of an abbot (Abbot Suger) to physically manifest the divine importance of light in the architecture of his church, increasing the proportion of voids in church walls became a necessity. Churches constructed in the solid masonry technique of the time had load-bearing walls, and there was a desire to create more openings in church walls. This aim led to the emergence of a new architectural element known as "flying buttresses" (Roth, 2000; Müller & Vogel 2005). Flying buttresses supported the solid masonry walls of churches from the outside, preventing them from collapsing under the roof load and allowing more openings in the load-bearing walls. When used in conjunction with pointed arches and ribbed vaults, flying buttresses facilitated the construction of structures with desired ceiling heights. Unlike barrel vaults, where the height-width ratio is fixed, pointed arches allow for flexibility in adjusting the height and width of the arch. Thus, faith once again prompted the emergence of a new architectural element in the structural design.

Towards the late 14th century and the 15th to 16th centuries, “scholastic thought” gave way to “critical thinking”. The era in which structural advancements were influenced by faith neared its end. In the new era, on one hand, there was a belief in human intellectual capacity, leading artists to be perceived as philosophers engaged with stone. On the other hand, the enrichment of medieval cities through trade gave rise to a wealthy merchant class commissioning public buildings independent of religious authority for their cities and citizens. Ancient Greek and Roman artifacts began to be re-examined. This period of enlightenment is termed the Renaissance, meaning "rebirth."

During the Renaissance, there wasn't a significant development in building materials or structural systems. Still, the dome of the Santa Maria del Fiore Cathedral in Florence, completed by Filippo

Brunelleschi between 1420–1434, stands out for pushing the limits of construction technologies and structural possibilities. Known as a "self-supporting" dome, it is considered one of the first important architectural achievements of the Renaissance, boasting a span of 45 m, which was the largest span achieved with masonry construction up to that time (Figure 14).

Constructed as an octagonal vault, the first 3 m of the dome was built with solid stone, while the remaining part was constructed with a double shell to accommodate passages and stairs. The dome's hollow design and use of bricks as building material were crucial for reducing the load on the supporting structure. The inner and outer domes are connected by 24 ribs, contributing to the dome's stability (Figure 15). Another significant construction strategy was the creation of the dome's shells using a herringbone pattern, known as "fishbone," which enhanced its structural integrity (Bartoli, Betti, & Borri, 2015).

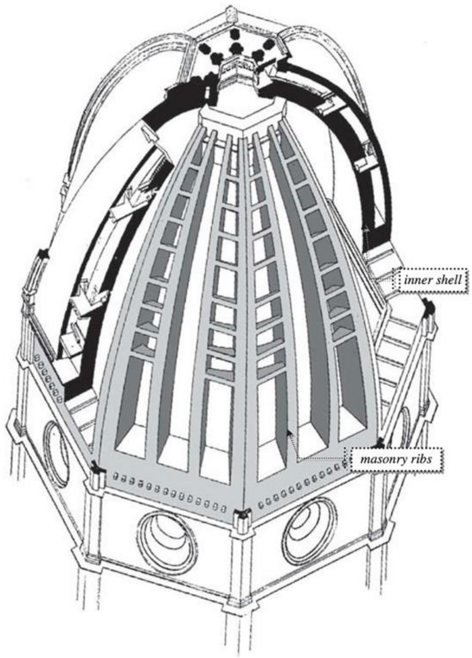

Figure 14. The dome of the Santa Maria del Fiore Church (Bartoli, Betti, & Borri, 2015).
Figure 15. Brunelleschi's Dome: axonometric view (Bartoli, Betti, & Borri, 2015).

These structures demonstrate the limits of masonry structures. Additionally, the Renaissance period prepared the intellectual groundwork necessary for the Industrial Revolution that would occur in the 18th century, impacting significantly on building materials and construction systems. Significant scientific advancements in the 17th and 18th centuries facilitated the subsequent development of architectural design. Galileo Galilei's publication in 1638, "Dialogues relating to two new sciences," laid the foundation for structural analysis with its approach to material strength and object motion. Robert Hooke's law in 1676 provided a scientific explanation for the flexibility of materials and their behavior under load. Sir Isaac Newton's publication of "Philosophiæ Naturalis Principia Mathematica" in 1687 established the laws of motion, contributing to the understanding of fundamental principles in structure. Independently, Newton and Gottfried Leibniz developed the fundamental theory of calculus, a method widely regarded as one of the most important mathematical tools in engineering. In 1750, Leonhard Euler and David Bernoulli developed the Euler-Bernoulli beam equation, a foundational theory underlying many structural engineering designs. Additionally, they developed the "theory of virtual work," a tool using force equilibrium and geometric compatibility to solve structural problems (Url-1, 2024).

3. MACHINE AGE: BUILDING IN THE LIGHT OF MODERN SCIENCE AND ENGINEERING

In the 17th and 18th centuries, the development of modern science introduced a new perception regarding the relationship between humans and the universe. The functioning of the universe became discoverable by the human mind, and these discoveries could be utilized to improve human life. With this perspective, significant social and technological changes/developments occurred in the Western world during the 18th century, affecting social life and consequently the architecture and structural system of the buildings.

Starting in the late 18th century in England, Europe, and North America production increased, and the number and population of cities grew due to the Industrial Revolution. A new urban society emerged, encompassing middle-class and working-class cultures. As society's lifestyle changed, there arose a need for new buildings and architectural typologies (Nuttgens, 1983).

In 1779, the first cast iron bridge (the Coalbrookdale Bridge) was built by Abraham Darby over the River Severn in England (Figure 16). The bridge spans 30.5 m (Tang, 2007); and by combining five arches side by side, it reaches a width of approximately 8 m, demonstrating the possibilities offered by iron as a structural material (Hodson, 2002).

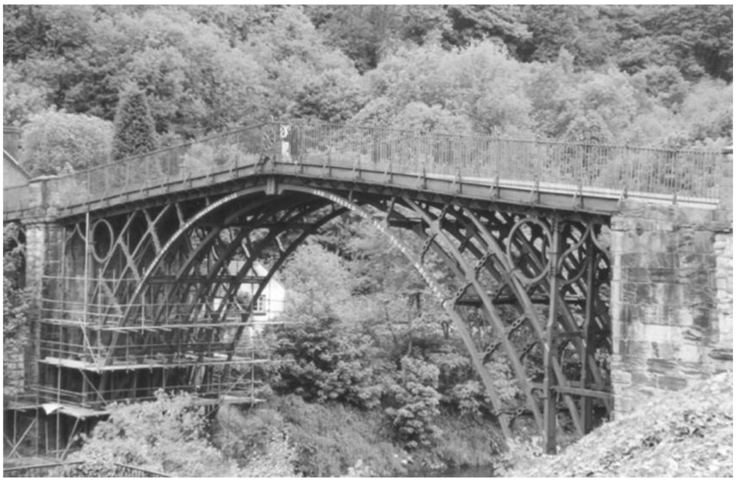

Figure 16. Iron Bridge, 1779, Coalbrookdale-England (The Ironbridge: An ASM Historical Landmark, 2012).

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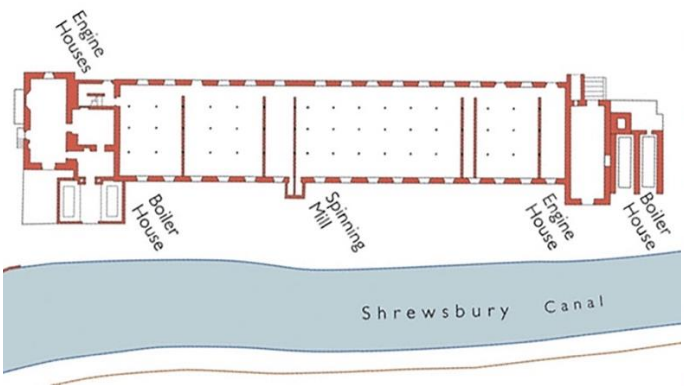
Between 1792 and 1793, in the city of Derby, England, iron structures began to be used in the construction of a cotton factory to provide fire resistance. Designed by William Strutt, the cotton factory structure consisted of iron columns, solid masonry walls, plastered wooden beams, and brick vaults. However, the first complete steel frame structure was built in 1796 in the city of Shrewsbury, England, by Charles Bage (Figure 17) (Yates, 2016; Sutherland, 1997).

Figure 17. View from south-east c.1900 (Yates, 2016).

This five-story factory incorporated all of Strutt's fire-resistant construction features and additionally used cast iron beams instead of wooden beams. Thus, the first multi-story iron-framed structure was built. This building became a precursor to many iron-framed structures to be built (Sutherland, 1997). Figures 18 and 19 illustrate the plan and section of the factory.



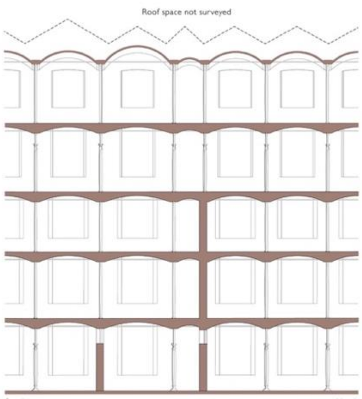


Figure 18. The first iron-framed structure designed by Charles Bage, the plan of the Flax Mill Shrewsbury, England, 1796 (Yates, 2016).
Figure 19. The section of the Flax Mill Shrewsbury, England, 1796 (Yates, 2016).

A pioneering structure that expresses the qualities and quantities of iron structures and their impact on architecture was the Bibliotheque Sainte-Genevieve library in Paris, designed by Henri Labrouste, between 1842-1850 (Figure 20).

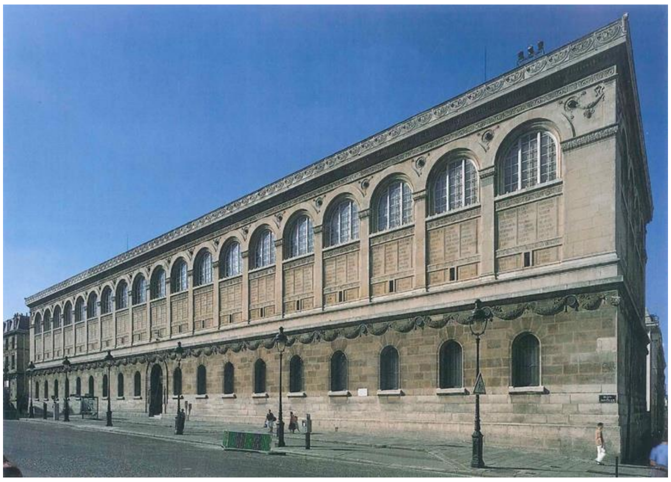


Figure 20. Bibliotheque Sainte-Genevieve, 1842–1850, Paris (Moffett, Fazio, & Wodehouse, 2004).

The ceilings of the structure were formed by arches, vaults, and domes, which were supported by iron columns and perimeter walls. The reading rooms of the building were covered with two parallel barrel vaults supported by wrought iron cage body arches (Figure 21, Figure 22). These vaults were anchored to the stone piers of the perimeter walls, while the transfer of load in the center of the space was achieved by cast iron columns (Belier, Bergdoll, & Coeur, 2012). The material and type of the structural system have an impact on the architectural form, and pioneering future with the use of metal in architecture.

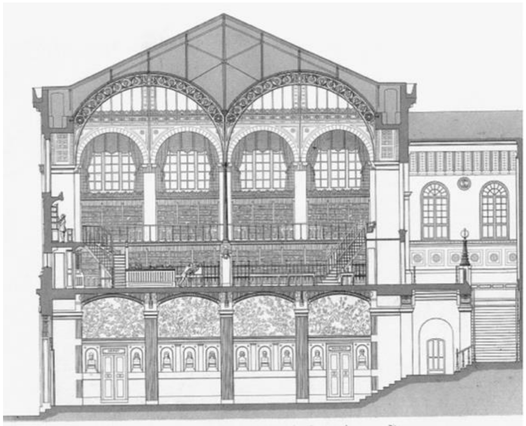



Figure 21. Cross-section of the Sainte-Geneviève Library (Bressani & Grignon, 2005).
Figure 22. View from the reading room of the Sainte-Geneviève Library (Moffett, Fazio, & Wodehouse, 2004).

Another iconic building type of the era is undoubtedly the railway. In 1830, the "Crown Street Station" was built in Liverpool. It was the first passenger train, used for passenger and freight transportation between the cities of Liverpool and Manchester. In the ongoing period, parliamentary buildings, museums, department stores, and industrial exhibition halls became frequent building types of the commercial society of the 19th century (Tietz, 1999).

Built in 1851 to host an international industrial exhibition, the Crystal Palace was another building that brought many innovations to its era in terms of structure. The Crystal Palace was constructed almost entirely from glass panels, with modular cast iron columns and beams forming a frame. The entire structure covers an area of 563.3 m x 124.4 m (Roth & Clark, 2014). The cast iron columns were positioned with a span of 14.6 m. In Figure 23, the positioning of columns on the ground floor of the Crystal Palace can be seen.

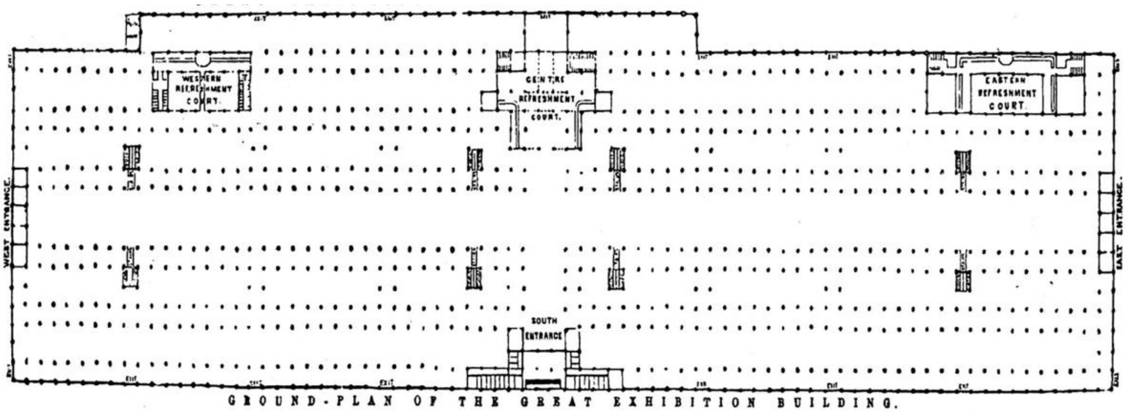


Figure 23. Ground floor plan of the Crystal Palace, 1851, London (López, 2014).

The designer of the structure, Joseph Paxton, implemented cross-bracings with wrought iron bars in the upper parts of the structure to resist lateral wind pressure. Additionally, the structure is designed to be dismantled and reassembled (Roth & Clark, 2014).

The construction of multi-story, rigid steel-framed buildings gained momentum in the United States following the Great Chicago Fire of 1871, which destroyed a large part of the city. Accordingly, reconstruction efforts began in the city. In this conjunction where work on fire-resistant iron-framed structures gained popularity, the Home Insurance Building, considered the first skyscraper today, was constructed (Figure 24, Figure 25) (Nuttgens, 1983; Tietz, 1999).

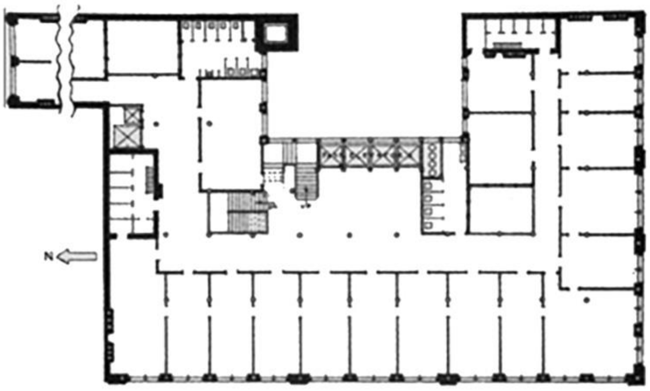


Figure 24. View of the Home Insurance Building (left) Chicago, 1883–1885 (Larson & Geraniotis, 1987).
Figure 25. Home Insurance Building typical floor plan (right) Chicago, 1883–1885 (Larson & Geraniotis, 1987).

The Home Insurance Building, designed by William Le Baron Jenney, was initially 10 stories tall and reached 12 stories with the addition of two more floors in 1890. The structure features cast and wrought iron columns, cast iron beams, and thick masonry walls for stability against horizontal loads (wind loads) (Craighead 2009).

Until the construction of the Monadnock Building in 1891, vertical loads in tall office buildings were supported using iron-steel columns and beams, while horizontal loads still relied on massive masonry walls (Deplazes, 2005). The 16-story Monadnock Building (1891-1893) with its brick masonry walls, reaching a thickness of 1.83 m at ground level, marked the limits of using solid masonry walls against horizontal loads in tall structures. Structural engineers adapted the 'trusses', which were commonly used to resist horizontal loads in bridges and formed by the convergence of diagonal bars, to tall office buildings to solve this problem. These structural elements, which provide stability against horizontal loads, were named 'steel diagonals' in buildings (Leslie, 2013). Thus, the massive masonry walls providing resistance to horizontal loads gave way to steel diagonals, which, together with steel columns and beams, formed rigid steel-framed high-rise structures.

The Masonic Temple (Figure 26), Old Colony Building (Figure 27), and Reliance Building (Figure 28), all designed by the architectural firm of Burnham and Root, are among the first examples of rigid steel-framed steel systems consisting of steel diagonals, steel columns, and steel beams (Leslie, 2013).

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Figure 26. Masonic Temple, 1892, Chicago (left) (Leslie, 2010).
Figure 27. Old Colony, 1895, Chicago (centre) (Leslie, 2010).
Figure 28. Reliance Building, 1895, Chicago (right) (Leslie, 2010).

In the late 19th century, while rigid steel frame systems continued to be used in Europe and America, a construction engineer Vladimir Shukhov, specializing in industrial steel structures in Russia, presented a different approach to steel structures. Shukhov used steel to form double-curved shapes, which we now call hyperboloid structures, by working on non-Euclidean geometries. He obtained a patent for the system, which we might refer to today as 'steel shell structures' but which he termed 'metal lace,' in 1899 (English, 2005; Kamal, 2020). Figure 29 shows plan drawings of a reticular roof patent application and Figure 30 shows section drawings of a reticular roof patent application.

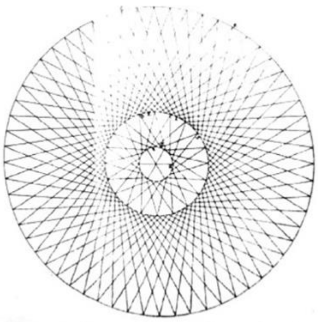
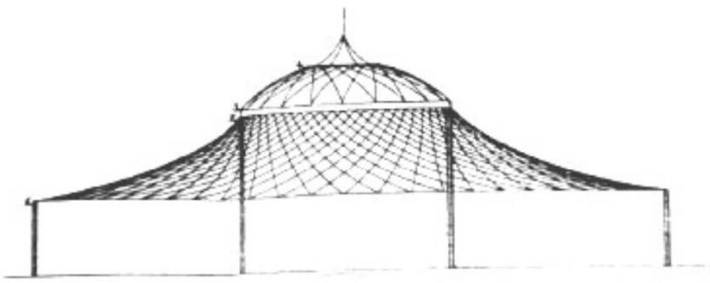

Figure 29. Plan drawings of a reticular roof patent application, 1895 (English, 2005).
Figure 30. Section drawings of a reticular roof patent application, 1895 (English, 2005).

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Steel shell structures are created by assembling steel linear elements with bolts and/or rivets to form diamond-shaped cells. The advantages provided by grid shell structures compared to other structures include reduced structure weight, reduced uniaxial stress in structural elements (compression or tension), high load-bearing capacity, and simplification in production and assembly (English, 2005).

The hyperboloid roofs of the exhibition pavilions at the 1896 Russia Industrial and Handicrafts Exhibition in Nizhny Novgorod were the first public examples of Shukhov's new system. The roofs of the exhibition pavilions were constructed from double-curved surfaces formed by a reticular framework of flat angle bars and flat iron rods. At the Nizhny Novgorod Exhibition, two pavilions of this type were built, one oval (Figure 31) and the other circular (Figure 32) (English, 2005).

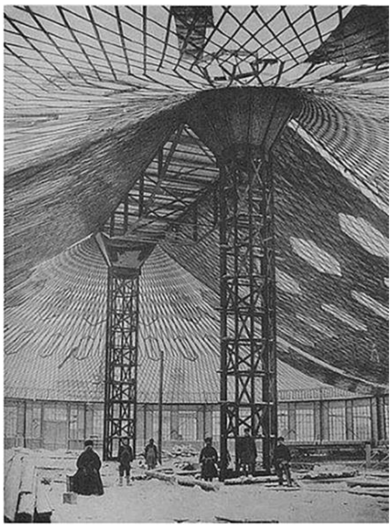
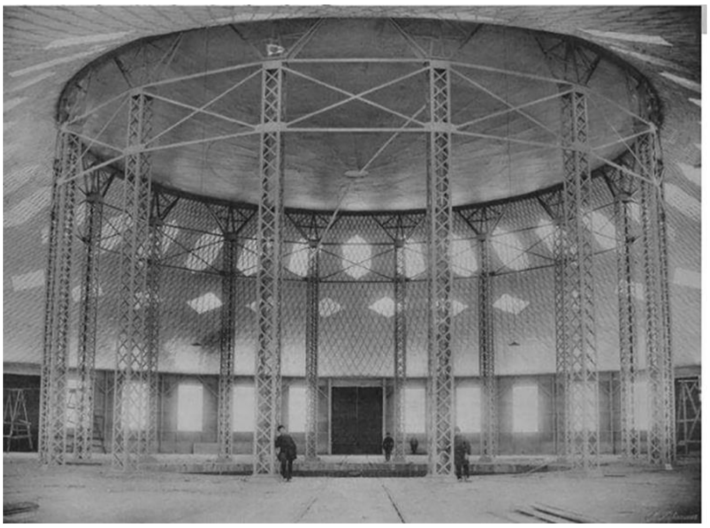

Figure 31. Oval pavilion of the Nizhny Novgorod Fair, 1896 (English, 2005).
Figure 32. Circular pavilion of the Nizhny Novgorod Fair, 1896 (English, 2005).

With the addition of reinforced concrete as a composite building material, to these advancements, the diversity in construction began to increase. Evidence of the early use of reinforced concrete dates back to as early as the 1840s. However, there is disagreement among researchers regarding the exact date and by whom reinforced concrete was first produced. Some of the names who obtained patents for reinforced concrete building materials include William Boutland Wilkinson in 1854, Frenchman Joseph-Louis Lambot in 1855, and Joseph Monier in 1877 (Wang, 2013; Marcos, San-José, Jose-Tomas, Santamaría, & Garmendia, 2018).

François Hennebique (1842-1921) obtained the patent for the Hennebique system in 1892. The Hennebique system based on transferring loads monolithically between the slab, beam, and column (Hellebois & Espion, 2013). Hennebique trained contractors about the Hennebique System and allowed licensed contractors to use the system. One of these contractor firms is Perret Frères. The son of the firm owner, Auguste Perret, built an apartment building, Franklin Apartment, in 1902 on Franklin Street using a reinforced concrete frame system (Figure 33). In many ways, this building served as a pioneering example for the subsequent use of reinforced concrete. (Gardner, 1997).

Figure 33. Facade of the Franklin Apartment, Paris, France (Moffett, Fazio, & Wodehouse, 2004).

The absence of load-bearing walls in the structure allowed for irregular placement of spaces in the floor plan. Thanks to the possibilities provided by the frame system, there are significantly more voids in the walls of the building's facade compared to structures built using load-bearing masonry construction techniques (Figure 34).

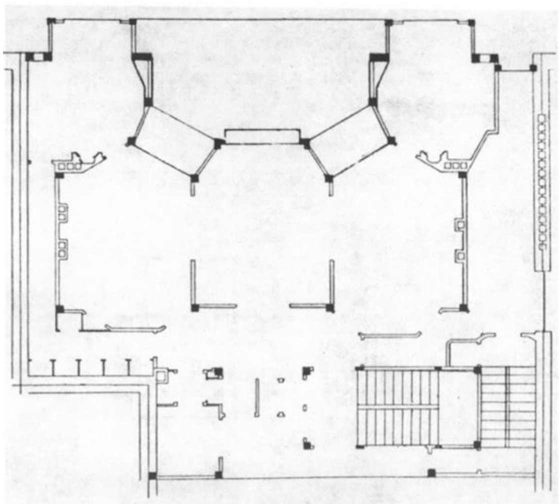

Figure 34. Plan of the Franklin Apartment, Paris, France, 1903 (Abram, 1987).

Although in this building, the reinforced concrete structural elements were covered with ceramics for various reasons, Perret, in 1905, openly revealed the reinforced concrete frame at 51 Rue de Ponthieu, by completely configuring the wall areas between the structural system with glass (Bressani, 1990; Tietz, 1999).

The shift away from the necessity of the outer wall to bear loads has prompted architects to reconsider the qualities of the building's outer walls, or building shells. In the early 20th century, architects began to question the continuation of window panes as a continuous membrane along the wall, separate from the rest of the structure (Murray, 2009). With this new perspective, one of the most impactful/innovative applications that emerged is the curtain wall system. An effective example of this approach to building envelopes is the Fagus Factory, designed by Walter Gropius and Adolf Meyer between 1911 and 1913.

Between 1914 and 1918, the years following World War I, the need for rapid housing due to the aftermath of the war laid the groundwork for the emergence of new architectural approaches. In this context, one of the revolutionary projects was the Dom-ino Project, which aimed at rapid mass housing. In the Domino Project, developed by Le Corbusier (Charles-Edouard Jeanneret), architectural form is reduced only to structure, and the interior and exterior walls of the building are not specified; they are considered as filling elements to be shaped according to the need of its users (Aureli, 2014).

In 1919, a design school ‘Bauhaus’ was founded by Walter Gropius in the city of Weimar, Germany. The basic approach of Bauhaus is to reintegrate art and production which was separated by industrialization (Nuttgens, 1983).

While the Bauhaus movement continued in Germany, Le Corbusier put forward the principles of the new architecture. He summarized his ideas in five points in his book "Vers une Architecture" (1923) and accordingly with his design of the "Villa Savoye" in Poissy (1928). Simultaneously, the constructivist movement in architecture started in Russia. El Lissitzky, an architect, drew inspiration from the constructivist movement in painting. Based on the idea of reducing architecture to only the most essential functional elements and shaping buildings according to their structural elements, El Lissitzky designed the Sky-hook project between 1923 and 1926 with the collaboration of Dutch architect Mark Stam (Figure 35).

Sky-hook, an office complex, is a horizontal skyscraper consisting of spaces positioned horizontally like bridges on three vertical shafts containing vertical circulation areas (Curtis, 1986; Tietz, 1999).

Figure 35. El Lissitzky: Sky-hook, 1924 (Lissitzky, 1970).

In the same years, the development of reinforced concrete systems continued. One of the most significant advancements in this regard was the patent for pre-stressed concrete obtained in 1928 by Eugène Freyssinet (1879-1962), a French construction engineer. Pre-stressing involves applying artificial opposite pressure to the pressure that a reinforced concrete structural element would normally be subjected to. With pre-stressed concrete, wider spans could be achieved using smaller cross-sections of reinforced concrete structural elements (Shushkewich, 2012). Additionally, during the same period, high-strength cement began to be used (Antonucci & Nannini, 2019).

In the second half of the 20th century, reinforced concrete continued to be utilized due to its technical capabilities, and structural-plastic-aesthetic properties. During this period, some pioneering architects and engineers working at the intersection of architecture and engineering contributed to the advancements in reinforced concrete construction technology through experimental studies. One of the architects who contributed to the reinforced concrete construction technique in this context is Pierre Luigi Nervi. Nervi designed a 94 m long transparent barrel vault to form the roof of the central hall of the Turin Exhibition Complex (Figure 36). He used the "ferrocement" technology, for which he obtained its patent in 1945, in the production of prefabricated elements of this vault. In the Ferrocement technique, also known as the Nervi system, a thin layer of concrete is reinforced with a thick mesh composed of small-diameter wires, resulting in the reinforced concrete element that is crack-resistant and highly ductile (Chiorino & Chiorino, 2011; Antonucci & Nannini, 2019).

Figure 36. P.L. Nervi, Central hall (Hall B) of Turin Exhibition Complex, Turin, 1948 (Chiorino & Chiorino, 2011).

During those years, Nervi also obtained a patent for ribbed floor slabs with an isostatic pattern. In this type of flooring, the floor beams are positioned along the isostatic lines of the slab. These lines define the primary tensile forces in the slab. The bending moments are tangent to the trajectories of zero rotational moments (torques). Nervi first applied this system in the projects of Tobacco Factories in Bologna (Figure 37) ((Antonucci & Nannini, 2019).

Figure 37. Concrete slabs of the tobacco factory, 1949-1933, Bologna (Antonucci & Nannini, 2019).

Between 1939 and 1945, World War II took place. After World War II on one hand, awareness about the absence of human emotions/facts in the rational architecture presented by modernism was raised, while on the other hand, it facilitated the transfer of technologies developed during the war to building technologies. In this context, the Raleigh Pavilion (Dorton Arena) (Figure 38), designed by Matthew Nowicki, proposed a new direction for building technologies and designs worldwide (Sprague, 2010).

Figure 38. Dorton Arena, 1954, Raleigh, Matthew Nowicki (Sprague, 2010).

The form of the arena is created by bringing together two reinforced concrete parabolic arches, supported by delicate columns, inclined at 25 degrees to the ground plane (Petroli 2021). Steel roof cables are suspended between these reinforced concrete parabolas (Figure 39). Instead of vertical walls and columns, the roof is supported by a network of steel cables (Brown, 2014).

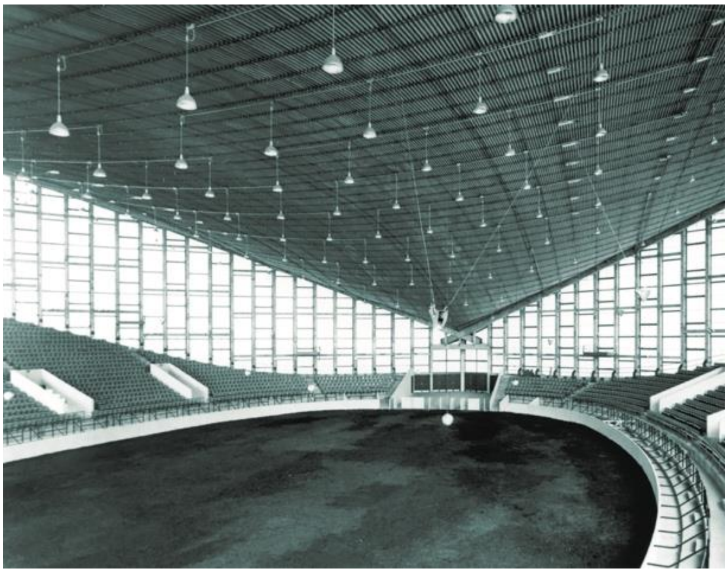

Figure 39. Interior view of Dorton Arena, 1954, Raleigh, Matthew Nowicki (Brown, 2014).

Underneath the intersection points of the arches, in addition to the legs of the two arches, a third vertical support element is used. This third support provides resistance to compression and/or tension loads under wind and/or snow loads. In other words, this tripod, created with the third support, is utilized to prevent the overturning of the intersection point under various loads. This ground breaking building is the first modern stadium to feature a permanent cable-supported roof (Brown, 2014).

Another architect who utilized advancing technology in building structures was Eduardo Catalano (1917–2010). He was a close friend of Nowicki. Catalano worked with advanced geometric forms to create transparency. With his project "Curved Surface Structures," he explored various combinations of hyperbolic paraboloid forms. By leveraging the technologies of aluminium and plywood that emerged as a result of wartime advancements, he emphasized ties between innovation and industrial production. The house he constructed as a result of his research, known as the "Catalano House," was formed by shaping three layers of laminated wood into a single hyperbolic paraboloid (Figure 40). This hyperbolic paraboloid shell, supported by supports slightly thicker than five inches, spanned an area of 27.43 m. The spaces of the structure were delineated by full-length glass curtain walls beneath the shell (Sprague, 2010).

Figure 40. Catalano House, 1953–1955, Raleigh (Sprague, 2010).

Felix Candela also worked on utilizing hyperbolic paraboloids as structural shells with a different building material in a different geography around the same time. The Spanish architect designed another pioneering example of hyperbolic paraboloids with the Cosmic Ray Laboratory located in Mexico in 1951 (Figure 41). The structure consists of three arches tracing a parabolic curve and two thin hyperbolic paraboloid shells between these arches. The shells are shaped to minimize bending moments in cross-section. The thickness of the shell, which spans 10.8 m according to the distribution of loads, is 37 mm at the base and reduces to only 19 mm at the highest point (Sprague, 2013).

Figure 41. Cosmic Rays Laboratory, 1951 (Garlock & Billington, 2014).

In the following years, Candela continued his design of reinforced concrete hyperbolic paraboloid shells. In 1958, he designed the Los Manantiales Restaurant located in Xochimilco, which consists of 8 hyperbolic shells radiating from a central point. These shells, spanning 45 m, are four centimetres thick. Another example of these shells from the same year is the Lomas de Cuernavaca Chapel (Pedreschi, 2008).

Eladio Dieste was a figure who stood out from other engineers with his work on curved shell surfaces. The material he employs and the forms he creates set him apart from his peers. Dieste developed the use of the catenary (chain curve) to produce more complex double-curved forms, and with this technique, he designed structures he named "Gaussian vaults." The catenary defines the natural shape taken by a suspended cable due to its weight, representing a form-active geometry where all forces are axial tension. Inverting the cable defines the geometry of a similarly active arch structure where forces are axial compression due to their weight (Pedreschi & Theodossopoulos, 2007).

The basic static analysis of a catenary vault reveals that even in long, slender vaults, compression forces are minimal; however, such vaults tend to exhibit bending under their weight. The Gaussian vault, on the other hand, leverages its form to resist bending. The geometry is defined by a series of catenary curves, each sharing the same spread point but with varying heights. As these catenary curves move along their starting points, they rise and fall. The resulting surface is doubly curved, reinforcing the vault and preventing bending. In structures of this kind, load resistance is achieved through the form itself (Pedreschi, 2008).

In 1960, Dieste designed and oversaw the entire design-build process of the Church of Atlántida in Atlántida, Uruguay. The roof of this church, constructed with brick material, features a Gaussian vault. The structure's walls had a wavy form (Figure 42). The complexity of the wavy walls and the Gaussian vault roof arises from structural feasibility and economic considerations. Building brick walls that do not require moulds was simpler compared to concrete construction. Moreover, using bricks as a local material was economical (Dieste, 1992; Pedreschi, 2014).

Figure 42. View of church of Atlántida, 1960, Atlántida-Uruguay (Pedreschi, 2014).

4. FREE FROM STRUCTURAL CONSTRAINTS: THE IMPACT OF COMPUTERS

As a result of advancements in warfare technologies during World War II, the first Computer-Aided Architectural Design (CAAD) systems were introduced in the early 1960s. Since then, CAAD has gradually expanded its application in architecture over time (Brand, 2013). This development has enabled the construction of structures that would not have been feasible with traditional approaches. One such structure is the Sydney Opera House, designed by Danish architect Jorn Utzon between 1957 and 1965. Construction was completed in 1973 (Figure 43). It stands as one of the early examples of post-war modern architecture.

Figure 43. Sydney Opera House (Hale & Macdonald, 2005).

The Sydney Opera House consisted of a unifying reinforced concrete podium with reinforced concrete shells on top of this podium. While pioneering structures with reinforced concrete shells had previously been built in Italy, Spain, and Mexico, the shells designed by Utzon were different from their predecessors because they were not self-support. The structural system for carrying them had not been determined during the design phase.

Prestressed, cast-in-place reinforced concrete beams were used to cover approximately 50 m span of the structure's platform. Cross sections of these beams vary according to load distribution (Forés, 2008; Stracchi, Cardellicchio, & Tombesi, 2023; Rybczynski, 2022). Shells of the building consisted of a ridge beam, prefabricated reinforced concrete beams extending to this ridge beam, and on-site assembled prefabricated shell pieces forming the upper covering. The precise placement of precast ribs has been achieved through the use of new construction methods and computer technology (Forés, 2008; Stracchi, Cardellicchio, & Tombesi, 2023; Rybczynski, 2022).

Completed around the same time as the Sydney Opera House in 1972, another significant structure that played a pivotal role in transitioning from physical models to computer-based models in architectural design is the Munich Olympic Stadium (Figure 44). This stadium covers an area of 75,000 square meters. The absence of pioneering lightweight structural constructions of this scale necessitated collaboration among experts from various disciplines, the development of new methods for structural analysis, and the mandatory adoption of emerging computer technologies of the time (Tomlow, 2016).

Figure 44. Munich Olympic Stadium, 1972 (Tomlow, 2016).

The roof covering of the Munich Olympic Stadium is based on the principle of supporting a 210 km long prestressed cable net with 80 m high pylons. Acrylic glass (acrylic) was used as the covering material for covering the cable net structure to ensure both flexibility and strength under wind loads (Figure 45). The acrylic tiles are 2.9 m long in each direction. Neoprene is used at junction points to provide buffered connections to the cables (Brand, 2013).

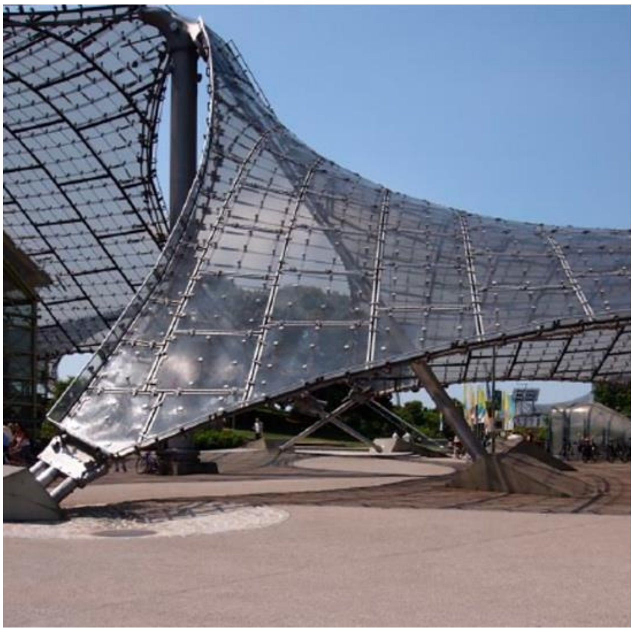

Figure 45. Munich Olympic Stadium, 1972 (Tomlow, 2016).

Throughout the second half of the 20th century, as mentioned before, advancements in digital technologies enabled the design and construction of structures that were not feasible using traditional methods. One of these structures is the Guggenheim Museum in Bilbao, Spain, designed by Frank Gehry (Figure 46). Similar to the Sydney Opera House and the Munich Olympic Stadium, the design and construction process of the Guggenheim Museum began with physical models and was completed using digital technologies.

Figure 46. View of the Guggenheim Museum, 1991–97, Bilbao-Spain (Rybczynski, 2022).

Additionally, similar to the Sydney Opera House, in the design stage of the Guggenheim Museum, the architect prioritized form and function. Decisions regarding the structural system and construction were explored after the project reached a certain maturity. This approach demonstrates that in the creation of a structure's form, the structural system is not a design constraint anymore.

The main structural system of the building was determined as a steel frame due to its ability to preserve the architectural form envisioned by the architect, its capability to provide rigidity against lateral loads, and its lightweight nature. Most of the steel structural elements were arranged regularly. To support the irregular shape of the external walls/shell, a secondary structural system and a connection system that integrates both systems were used. The angles and lengths of these connections varied to harmonize with the facade form. In other words, the distance between the primary and secondary structures varied (Yun & Schodek, 2003).

During the digital implementation process of the Guggenheim Museum, Conception Assistée Tridimensionnelle Interactive Appliquée (CATIA), a software originally developed for designing fighter jets, was utilized. Geometric data of the structure was imported into CATIA, which was then employed to streamline and rationalize the curved surfaces of the building. CATIA was also instrumental in determining the position and form of the structural system along the length of the building to support these curved surfaces of the building shell (Iyengar, Novak, Sinn, & Zils, 1998).

Due to the impossibility of incorporating the dimensional information of profiles belonging to the entire structure of CATIA software, BOCAD, which is a comprehensive detailing program, was used to generate three-dimensional graphic files of the structural framework of the building. Despite the variation in geometries of steel elements at nodal points, the connection plates, bolts, element slopes, etc., the entire frame could be drawn in three dimensions by editing a few elements in another program and adding them to BOCAD. Detailed fabrication drawings and details were almost flawlessly created from these entirely three-dimensional data (Iyengar, Novak, Sinn, & Zils, 1998).

The design and construction methods of the Guggenheim Museum in Bilbao not only made it well-known in its region but also increased the global recognition of the city of Bilbao, attracting visitors from various parts of the world. In the 20th century, the advancement of digital technologies not only influenced the design and construction phases of buildings but also enabled these structures and their designers to gain global fame through evolving modern media tools. With all these dynamics, Frank Gehry's design of the Guggenheim Museum in Bilbao contributed to the emergence of the 'starchitect' concept (Rybczynski, 2022).

By the late 20th century, the priority in the design and construction process was not so much about exploring the limits of materials and technology, but rather about being able to think the previously unthinkable. At this point, another architect often referred to as a 'starchitect', Zaha Hadid (1950–2016), showcased her vision and perspective by breaking away from conventional forms and structures by her building designs in various cities throughout the world.

One of Zaha Hadid's most striking structures is the Heydar Aliyev Cultural Centre, located in the heart of Baku, the capital of Azerbaijan, on the shores of the Caspian Sea (Figure 47). This building, characterized by undulating white shapes, houses a concert hall, a museum, and a national library. A continuous promenade inside the building connects lobbies belonging to different uses.

Figure 47. Heydar Aliyev Cultural Center, Baku, Azerbaijan. Zaha Hadid Architects, 2007–12 (Rybczynski, 2022).

If Guggenheim Bilbao is known for its unexpectedly colliding forms, this curvilinear building by Hadid is distinguished by blurred boundaries and merging surfaces. Space appears infinite, floors blend into walls, walls into ceilings, and the interior merges with the exterior. The roofs, though they appear shell-like, are space frames supported by steel trusses. This intricate structure is concealed behind a cladding made of fiber-reinforced concrete panels. Surfaces twist, fold, and curve. The building's fluid organization is not tied to hierarchies or axes, and its scaleless architecture largely lacks details (Rybczynski, 2022). The structure is no longer an issue, no longer a determinant of form, instead becoming a subservient facilitator.

5. CONCLUSIONS

This study, based on the conducted literature review, analyzes the history of structures up to the present day through the concepts of "structural system," "construction material," and "structural innovation," considering the development of structures in the context of social dynamics. Throughout history, construction methods, materials, and technologies have evolved and developed in response to social needs and technological advancements. The building structures addressed in this study, are illustrated in Figure 48, including their types, materials, and the structural innovations they introduced.

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Era	Period	BUILDING NAME	BUILDING FUNCTION	STRUCTURAL SYSTEM	CONSTRUCTION MATERIAL	STRUCTURAL INNOVATION
Ancient to Medieval Periods	Neolithic Period	Çatalhöyük	Residential Cult Units	Masonry Structure	Mud brick	
	Sumerians (3200 BC-300 AD)	Ur Ziggurat (Circa 2100 BCE)	Temple	Masonry Structure	Mud brick	
	Ancient Egypt (3100 BC-300AD)	Step Pyramid of Djoser Saqqara-Egypt Circa 2750 BC	Funerary Structure	Masonry Structure/ Limestone	Limestone	Use of limestone as a building material
		Temple of Amun Hypostil Hall	Temple	Column-beam system using stone	Stone	One of the first examples of a column-beam system constructed with stone.
	Ancient Greek	Parthenon Temple (437-438 BCE)	Temple	Column-beam system using stone	Stone	
	Roman Empire	Pantheon Temple (118-128 BCE)	Temple	Masonry/concrete	Concrete	Innovative use of concrete
	Eastern Roman Empire	Hagia Sophia Church (6th century AD)	Church	Masonry Construction	Stone	Pendentive
	Medieval Period	The Monastery of Saint Martin (1001-1026)	Monastery	Masonry walls and stone arches	Stone	
	Gothic Architecture (12-15th century)	Royal Abbey Church of Saint-Denis (1140-1144)	Church	Masonry Construction	Stone	Flying Buttresses, Ribbed vaults Novel pointed arches rest on stone columns and piers
	15-16 th Century	Santa Maria del Fiore Church / Brunelleschi's Dome (1420-1434)	Church	Masonry Construction	Brick	span of the dome: 45 m The largest span achieved with masonry construction up to that time
Renaissance to 19th Century		Iron Bridge (1779)	Bridge	Iron structure Iron Arches	Iron	First iron bridge: demonstrating the possibilities offered by iron as a structural material
		Flax Mill Factory (1796)	Factory	Iron-Frame Structure	Iron	First multi-story iron-framed structure
		Bibliotheque Sainte-Genevieve (1842-1850)	Library	Hybrid: Cast iron structure with masonry elements	Iron & Stone	The material and type of the structural system have an impact on the architectural form, and pioneering the future use of metal in architecture.
		Crystal Palace (1851)	Exhibition Hall	Frame Structure Cast iron columns&beams	Iron	Precast structural elements Glass panels Cross-bracings for lateral wind pressure
		Home Insurance Building (1883-1885)	Office	Iron columns & beams Masonry walls for Stability against horizontal loads	Iron & Stone	First high-rise building structure
		Masonic Temple (1892) Old Colony (1895) Reliance Building (1895)	Office	Rigid Steel Frame Structure	Steel	Steel diagonals: massive masonry walls providing resistance to horizontal loads gave way to steel diagonals
		Oval and Circular pavillion of the Nizhny Novgorod Fair (1896)	Exhibition Hall	Tensile Structure	Steel	Steel was used to form double-curved shapes, which we now call hyperboloid structures, by working on non-Euclidean geometries.
Early 20th Century		Franklin Apartment (1903)	Residential	Reinforced concrete frame system	Reinforced concrete	Subsequent use of reinforced concrete as a frame system material
		Central Hall of Turin Exhibition Complex (1948)	Exhibition Hall	Reinforced concrete vault	Reinforced concrete	Invention of ferrocement technique
		Bologna Tobacco Factory (1949)	Factory	Reinforced concrete frame system	Reinforced concrete	Ribbed floor slabs with isostatic pattern
Late 20th Century		Dorton Arena (1954)	Stadium	Parabolic arches, supported by columns Roof: Tensile structure	Steel & Concrete	First modern stadium to feature a permanent cable-supported roof
		Catalano House (1953-1955)	Residential	Shell Structure	Laminated wood	Hyperbolic paraboloid shell
		Comic Rays Laboratory (1951)	Laboratory	Shell Structure	Reinforced concrete	Hyperbolic paraboloid shell
		Church of Atlantida (1960)	Church	Brick Walls & Gaussian vault roof (Shell)	Brick	Invention of gaussian vault
		Sydney Opera House (1957-1973)	Opera House	Shell:Precast RFC shells carried by precast RFC ribs Platform: Reinforced concrete frame	Concrete	Computational analysis software was significantly used for the first time by structural engineers
		Munich Olympic Stadium (1972)	Stadium	Tensile Structure	Steel & Acrylic glass	A pioneering tensile structure considering covering area and its construction time. Necessitated emerging computer technologies of its time.
		Bilbao Guggenheim Museum (1991-1997)	Museum	Steel Frame	Steel	With the help of computational technologies, in the design process of structure, the structural system is not a design constraint anymore. Decisions regarding the structural system and construction were explored after the project reached a certain maturity. The term starchitect was first applied to Frank Gehry, architect of Bilbao Guggenheim Museum.
21th Century		Heydar Aliyev Cultural Center (2007-2012)	Cultural Center	Concrete structure combined with steel space frame system	Concrete & Steel	The structure is no longer a determinant of form, instead becoming a subservient facilitator.

Beginning of the Renaissance: “scholastic thought” gave way to “critical thinking”. The era in which structural advancements were influenced by faith neared its end. Significant scientific advancements were occured.

1856: Invention of steel

World War I (1914-1918) World War II (1939-1945)

Invention and advancements in reinforced concrete as a structural material

BUILDING FOR FAITH: THE LIMITS OF TRADITIONAL MATERIALS

As settled living began, ritual spaces were built, and belief systems became an important dynamic that pushed the boundaries of building technologies through the early civilizations.

Structural innovations emerged for the construction of religious buildings. These buildings were constructed at the limits of existing construction technologies.

Untill Renaissance, faith was the motivation for advancements in construction technology.

Beginning of the Industrial Revolution: The emergence of new building typologies in industrial society: bridges-railways, factories, exhibition halls, office buildings Emergence of new materials and construction techniques.

MACHINE AGE: BUILDING IN THE LIGHT OF MODERN SCIENCE AND ENGINEERING

Additionally construction of new built environments developed for new urban society, with the use of military technologies in the construction sector, there was a significant increase in the diversity of building materials and construction techniques.

Despite the construction of many buildings with various architectural styles, structural design boundaries continued to dominate the design of buildings.

This situation persisted until computer technology became actively used in building design and production.

As a result of advancements in warfare technologies during World War II, the first Computer-Aided Architectural Design (CAAD) systems were introduced in the early 1960s.

FREE FROM STRUCTURAL CONSTRAINTS: THE IMPACT OF COMPUTERS

Development of digital technologies enabled the construction of structures that were previously impossible to design and construct using traditional methods.

Possibilities which computational technologies offer and existance of structures which began to give global recognition to their designers fuelled a desire to achieve what had not been done before. Accordingly, the term "Starchitect" was emerged as a indicator which shows the importance of "fame".

Structural system capabilities are no longer a design constraint.

Figure 48. The building structures examined in the study.

Traditional construction materials and structural systems were used in building construction from the beginning of the Neolithic period to the Enlightenment era. In this period, building structures that pushed the boundaries of that time's construction technologies were constructed with a motivation rooted in faith. Examples of such structures include the ziggurats of the Sumerians, the pyramids of the Egyptians, and the temples of the Greeks and Romans. It is crucial to state that while many necessary civil architecture products were constructed during these periods, monumental structures that challenged technological limits were primarily religious buildings. The belief in an afterlife was a significant motivation for constructing stone pyramids; the Greeks produced monumental examples of column-beam stone systems in their magnificent temples dedicated to the gods. In the Roman period, concrete, used as construction material in public buildings, was employed in its most effective form to span the biggest opening achieved to date in the Pantheon Temple, dedicated to all gods. Gothic architecture, with its notable examples of masonry construction, emerged from the desire to incorporate divine light effects into church interiors.

With the Enlightenment and the subsequent Industrial Revolution, iron and steel began to be used as new construction materials. Although these new materials were initially employed with traditional construction techniques without understanding their potential, by the time they facilitated the development of frame structures. During the same period, the changing lifestyle of society led to the emergence of new building types, and by the late 19th century, the use of reinforced concrete, a composite material, in frame systems brought a new dimension to building production and construction practices.

Particularly at the beginning of the 20th century, the opportunities provided by new building materials and construction techniques began to be utilized more effectively. For instance, in the first half of the 20th century, buildings started to be constructed without masonry thick walls through the steel cross-bracing that provided horizontal load resistance. In the second half of the 20th century, the ease of shaping reinforced concrete allowed for use in shell structures, especially in hyperbolic paraboloid shells. With advancements in reinforced concrete and steel materials, architects significantly addressed the problem of spanning openings without vertical supports, which had long posed a major structural constraint.

During the 20th century, marked by both world wars, the architectural effects following World War I were focused on architectural styles, while technological advancements after World War II focused on construction technologies. On the one hand, new construction materials like aluminum began to be used; on the other hand, advances in engineering science and emerging computer technologies had considerable effects on structural design. Indeed, the development of computer technologies has led to necessary advancements in structural design, with some suggesting that these advancements are as impactful as those brought about by the Industrial Revolution.

Emerging computer technologies first made a significant impact during the construction of the Sydney Opera House. This iconic structure, which won a design competition in 1957, was completed in 1973. Due to the lack of structural system considerations during the design phase, the project was successfully executed thanks to computational analysis software which had not been previously utilized. This landmark building set a precedent for projects where the structural system was not considered during the design phase. In the ongoing process, computer technologies have started to be used in various ways in building design and construction phases. These technologies are sometimes applied during the construction phase of a building while at other times, they enable the execution of a building that is designed without considering the structural system in the design phase. One such example is the Guggenheim Museum in Bilbao, which earned its architect the title of "starchitect."

Computational technologies have not only removed constraints from structural design but have also made digital design possible. Parametric designs by Zaha Hadid, who is also known as a "starchitect," clearly showcase the current state of architectural and structural design. Additionally, these technological advancements and globalization have facilitated the recognition of buildings and designers regardless of geographical location, making the creation of unique and unprecedented designs a new source of motivation.

In summary, an examination of structural developments up to the present day reveals that from the Neolithic period to the Industrial Revolution, structural innovations were driven by religious motivations and were constructed within the limits of masonry construction systems. Between the 18th and 20th centuries, following the Industrial Revolution and mechanization, the introduction of new building materials and advancements in engineering science led to the diversification and development of structural materials and systems. From the second half of the 20th century onward, innovations in structural systems facilitated by emerging digital technologies have shown that these systems no longer pose constraints for architectural designers (Figure 48).

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