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Considerations for Space Grid Structures: Comprehensive Review of Key Design Aspects and Developing Trends

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Abstract

The investigation aimed to identify key directions for advancing space grid structures. It involved a comprehensive survey of existing structural solutions, nodal connections, and design features specific to spatial rod structures. The analysis included theoretical, numerical, and experimental studies on the stress-strain state, factors influencing it, geometric optimization, and design principles. The focus was on space grid structures, particularly structural plates and their prevalent nodal connections. The investigation revealed that scientific and technological progress, such as improvements in material properties, calculation methods, and software simulations, significantly contributed to the advancement of structural designs by enhancing accuracy and reducing complexity. Geometric dimensions of modular elements and the height-to-span ratio were identified as key parameters affecting structural efficiency. The study also examined global experiences in nodal connection development and provided a general classification of such connections. By identifying advantages and disadvantages of existing space grid structures, potential pathways for further improvement were illuminated. The findings underscored the importance of developing innovative nodal connections as a primary avenue for enhancing space grid structures.

1. Introduction

The construction industry faces significant challenges in efficiently constructing large-span buildings and structures. Inefficient practices, technical constraints, and suboptimal material utilization contribute to the complexities and wastage within the field. The outdated techniques and designs have become morally and physically obsolete, resulting in increased costs and prolonged construction timelines. Therefore, there is an urgent need to enhance and explore new load-bearing structures, specifically space frames, which have the potential to significantly reduce material consumption and simplify manufacturing and installation procedures.

To address this need, conducting a comprehensive examination and learning from worldwide experiences and research on space grid structures is crucial. By studying these structures, valuable insights can be gained to develop innovative concepts for novel space systems. These systems should not only inherit the advantages of existing space frames but also possess unique characteristics, benefits, and specific features of their own. A thorough exploration of space grid structures will establish a solid foundation for developing groundbreaking concepts that can revolutionize the construction industry.

By leveraging the knowledge obtained from studying space grid structures, we can effectively overcome the complexities and inefficiencies associated with constructing large-span buildings. Implementing new load-bearing structures, such as advanced space frames, will result in significant savings in material usage, streamlined manufacturing processes, and simplified installation techniques. Ultimately, these advancements will lead to more cost-effective and time-efficient construction projects, setting the stage for a new era of innovation and sustainability in the construction industry.

2. Methods

The research focuses on space grid structures in the realm of architectural and structural design. The materials used in the study include textbooks, documents, research articles, and other relevant sources that provide information on the characteristics, advantages, and applications of space grid structures. These materials serve as the basis for the literature review and analysis conducted in this manuscript.

The data for this study were collected through a comprehensive review and analysis of existing literature and research articles on space grid structures as well as authors' manuscripts.

The research design employed in this manuscript is a descriptive and analytical approach. It involves a thorough literature review and analysis of the characteristics, advantages, and applications of space grid structures. The research design aims to provide a comprehensive understanding of the subject matter by examining existing knowledge and identifying trends, challenges, and future directions in the field of space grid structures.

The study begins with an overview of the emergence and recognition of space grid structures in the field of architectural design. It highlights their aesthetic appeal, cost-effectiveness, lightweight nature, and enhanced productivity compared to conventional structural alternatives. The manuscript then explores the advantages of space grid structures, including their sufficient stiffness, versatility in shape possibilities, and historical development.

Furthermore, the manuscript delves into the design aspects of space grid structures, particularly focusing on the selection of geometric parameters such as depth and module size. It discusses the interdependence between these parameters and their influence on structural design and cost-effectiveness. The study also examines the challenges associated with nodal connections in space grid structures and the development of efficient and reliable constructive solutions for these connections.

The research design concludes with a comprehensive analysis of existing knowledge and practical developments in the field of space grid structures. It highlights the contributions of the academic community in advancing constructive solutions, calculation methods, and structural optimization techniques. The manuscript concludes by discussing the prospects and opportunities for space grid structures in the realm of large-scale structural systems.

In summary, this manuscript employs a descriptive and analytical research design, utilizing literature review and analysis as the primary method for data collection. The study aims to provide a comprehensive understanding of space grid structures, their advantages, challenges, and future directions in architectural and structural design.

3. Results and Discussion

Currently, space grid structures have emerged as the predominant and widely recognized systems within the realm of space frames. Their extensive acknowledgment and proliferation stem from their remarkable ability to achieve aesthetically pleasing and precisely defined configurations, as evidenced by the presence of numerous distinctive and extraordinary structures on a global scale (Furche, 2016; Li & Taniguchi, 2019; Lapenko et al., 2020; Piana et al, 2021; Abedi & Sheidaii, 2022). The use of these space grid structures offers a multitude of advantages, making them highly cost-effective when compared to conventional structural alternatives (Gomez-Jauregui et al, 2018). The lightweight nature of space grid structures is a primary advantage that sets them apart from other design alternatives (Chilton, 2000; Allen & Iano, 2013). This advantage arises from the efficient load transfer mechanism that primarily relies on axial tension or compression, ensuring optimal utilization of materials within each element. Additionally, the predominant use of aluminum or composite components further contributes to reducing the overall self-weight of these structures.

Enhanced productivity is another notable advantage offered by space grid structures. These structures are constructed using standardized prefabricated units that exhibit consistent size and shape. Leveraging industrialized manufactured lines, these units are efficiently produced in factories. Furthermore, the ease of transportation and swift on-site assembly by semi-skilled labor, employing conventional equipment and machinery, enhances the efficiency of the construction process. As a result, space grid structures can be erected at a lower cost, benefitting from increased productivity associated with this innovative approach.

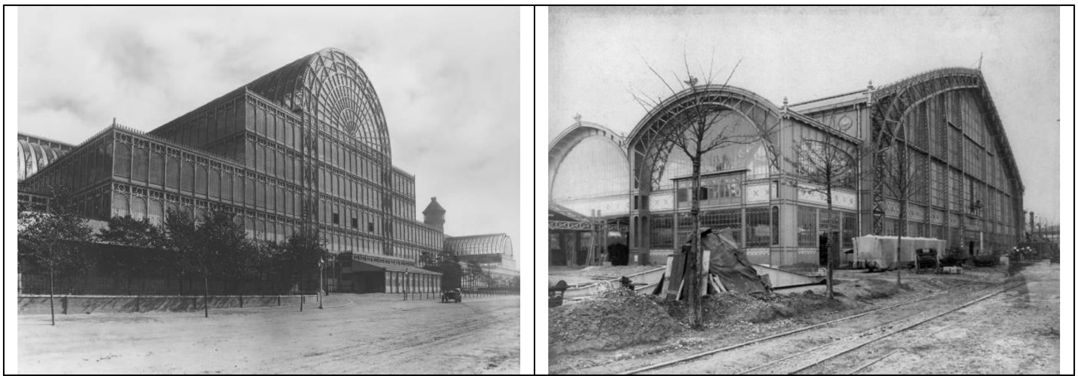
Despite their lightweight composition, space grid structures exhibit sufficient stiffness. This notable characteristic can be attributed to their three-dimensional nature and the full engagement of their components. Such structures demonstrate excellent rigidity and stiffness, allowing them to effectively withstand unsymmetrical or concentrated loads as well as local damage.

The versatility of space grid structures is yet another advantage worth noting. By utilizing modular units, these structures can take on various shapes, including spatial grids, lattice structures, and free-form configurations. This adaptability allows for a wide range of architectural possibilities while maintaining visual appeal characterized by clean lines and elegant simplicity.

The comprehensive analysis of these advantages showcases the exceptional appeal and potential of space grid structures in the realm of architectural and structural design. The lightweight construction, enhanced productivity, sufficient stiffness, and versatile shape possibilities make them an appealing option for a variety of applications. Continued exploration and implementation of these structures promise advancements and opportunities in the pursuit of innovative and efficient design solutions.

Space grid structures are renowned for their distinctive composition comprising mass-produced modular elements. The versatility of these structures allows for the adoption of various configurations, such as single-layer or dual-layer lattice shells, as well as flat plates. The form and relative positioning of the modular elements determine the ultimate shape of the space grid structure. An outstanding advantage of employing space grid structures lies in their ability to facilitate the construction of large-span roof systems with relatively shallow depths, typically ranging from 1/16 to 1/25 of the span. Furthermore, these structures have a lightweight nature and demonstrate reduced vulnerability to seismic forces, owing to the utilization of standardized, compact modular elements. The compactness characteristic greatly simplifies transportation, handling, and installation processes. Moreover, the utilization of modular components empowers architects to create visually captivating geometric shapes and surfaces that express the desired architectural aesthetics.

The merits of modular construction were substantiated over a century ago, evident in the design, manufacturing, and installation of iconic structures such as The Crystal Palace for The Great Exhibition in 1851 in London and The Galeries des Machines in Paris in 1889 (Chilton, 2000) (Figure 1). While flat double-layer grids often exemplify the prevailing class of space grid structures, numerous instances exist where space grid structures with intricate forms, including domes, vaults, stepped plates, and pyramids, have been successfully implemented (Allen & Iano, 2013). Such structures offer abundant opportunities for utilizing steel and composite materials in the construction of expansive buildings, enabling the realization of an extensive array of forms and shapes. Among the various types of space grid structures, flat double-layer grids emerge as particularly distinctive examples (Gemmerling, 2014). Tubular steel elements are predominantly employed in designing these structures, while steel profiles with alternative cross-sections, such as angles, channels, and thin-walled profiles, are less frequently utilized.



(a) **(b)**

Fig. 1 *Crystal Palace (a) (Crystal Palace | Description, History, & Facts, n.d.) and Gallery of Machines for Paris Exposition in 1889 (Gallery of Machines, Paris Exposition, 1889)*

The origins of space grid structures can be traced back to the groundbreaking contributions of Alexander Graham Bell, the renowned inventor, in the early twentieth century. During this era, Bell delved into the possibilities of constructing octahedral and tetrahedral spatial shapes using rods (Figure 2). He emphasized the exceptional qualities of three-dimensional grid elements, highlighting their impressive load-carrying capacity and minimal weight. However, it was not until the late 1930s that the first-generation space grid systems, later known as the Unistrut system, were officially patented. Despite these early advancements, space grid structures did not witness widespread adoption in the construction industry until the emergence of the Mero system in the early 1940s in Germany. Notably, the Mero system marked the first successful commercial implementation of a comprehensive spatial structure (Edmondson, 2007).

The mid-twentieth century witnessed a significant surge in the utilization of space grid structures, driven by the endeavors of architects and engineers who sought to explore novel and distinctive forms, as well as alternative joining techniques. One prominent contributor to the development of space structures was Richard Fuller, an American architect, engineer, and inventor, who introduced the concept of the geodesic dome (Bai & Yang, 2012) (Figure 3).

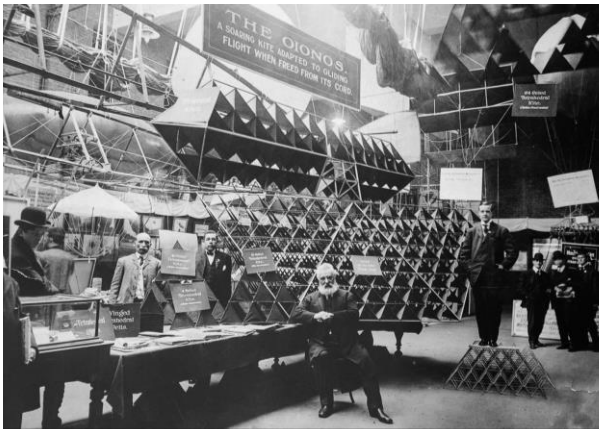
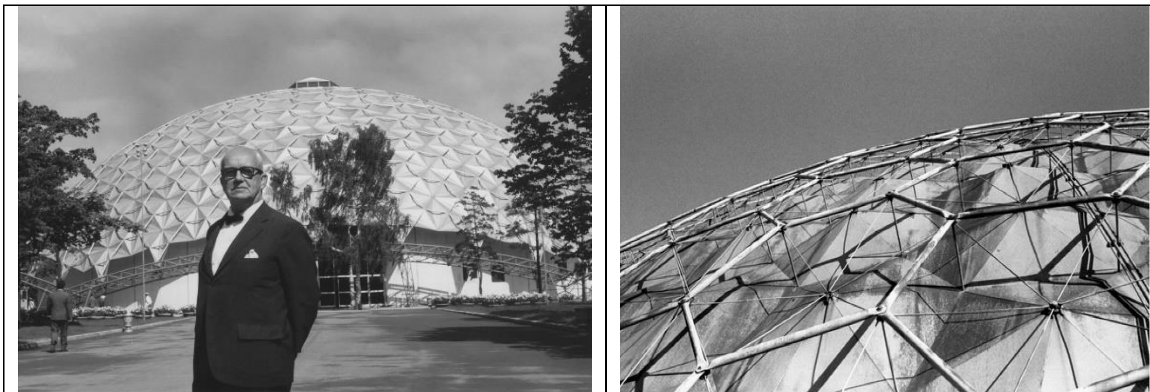


Fig. 2 *Bell poses with some of his tetrahedral grid structures (Alexander Graham Bell's Bizarre Tetrahedral Kites, 1902-1912 - Rare Historical Photos, 2021)*



(a)	(b)

Fig. 3 *Buckminster Fuller and his creations (The Story of Buckminster Fuller and the union tank car dome, n.d.; R. Buckminster Fuller | Engineer, Architect, Futurist, n.d.)*

In the late 1940s, K. Wachsmann devised the Mobilar system (Figure 4), a spatial structural system that deviated substantially from existing systems such as the Mero system and the Unistrut system. Setting itself apart with integrated nodes and flexible connection components, the Mobilar system offered a departure from the rigid and massive geometries of its predecessors. Continuous refinement of these systems throughout the 1950s led to the emergence of several other pioneering systems (Gerrits, 1998; Makowski, 2002; Yang et al., 2015).

However, the early stages of structural design development did not progress as rapidly and intensively as the present day. The complexity and time-intensive nature of calculations were significant constraints, primarily stemming from the degree of static indeterminacy. These challenges impeded the analysis process and limited the widespread utilization of space grid structures. Nevertheless, the advent of computer technology revolutionized the entire design approach, ushering in a new era of development for these structures. The availability of computer software facilitated the analysis of highly intricate dimensional structures with heightened precision and reduced computational time (Gasii et al., 2022). Consequently, over the past fifty years, the development of space grid structures has reached unprecedented levels of advancement.

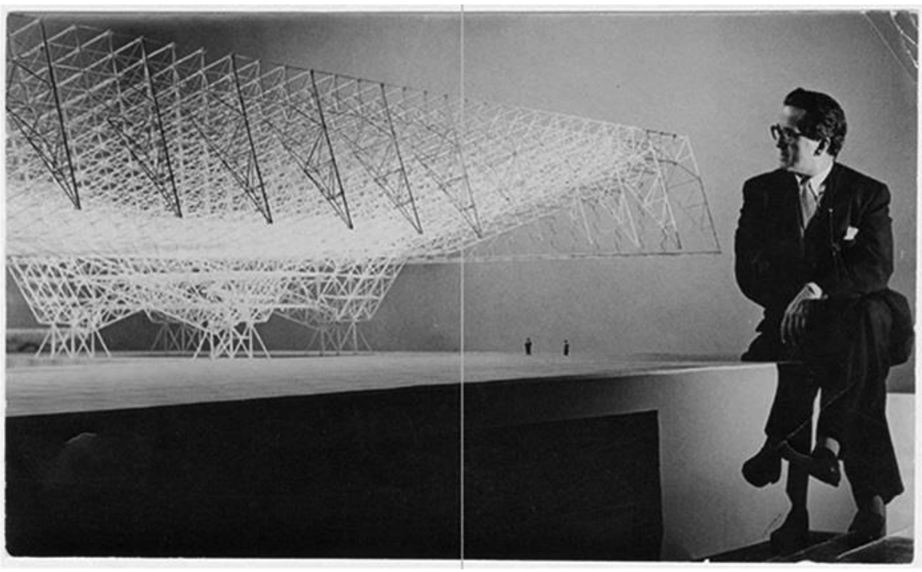


Fig. 4 *Konrad Wachsmann and his creations (Casas Prefabricadas Con General Panel System, Packaged Houses (1942-1947), Konrad Wachsmann, 2021)*

In addition to the evolution of computer technology, several other influential factors have played pivotal roles in the rapid progress of space grid structures. Firstly, the availability of advanced equipment and enhanced manufacturing capabilities has provided significant opportunities for the efficient production of these structures. Secondly, the demand for large indoor spaces, particularly in the context of mass sports and cultural events, meetings, and exhibitions, has consistently posed timely and pressing challenges, further driving the advancement of space grid structures.

The search for innovative structural forms capable of spanning large areas has been a central focus for architects, engineers, and scientists. Extensive theoretical and experimental investigations have been undertaken by numerous universities and research institutions worldwide, leading to significant advancements in the field. As a result, a considerable body of knowledge and practical developments has been translated into real-world applications.

Space grid structures have emerged as popular and creative solutions for various construction projects, including sports arenas, exhibition halls, transport terminals, and aircraft hangars (Liu et al., 2011). These structures exhibit a wide range of configurations, each with its distinct advantages and disadvantages. However, a common characteristic among all space grid structures is the reliance on modular elements subjected to axial compression or tension (Engel, 2009).

Despite the clear benefits and promising prospects of space grid structures, a major challenge lies in the complex manufacturing processes associated with nodal connections. In the pursuit of further advancing structural designs, there is a prevailing trend toward minimizing the variety of modular element sizes, simplifying installation procedures, and reducing the complexity of nodal connections.

As researchers and practitioners continue to explore the potential of space grid structures, a key focus is striking a delicate balance between structural efficiency and manufacturability. Efforts are being directed toward developing solutions that optimize performance while ensuring ease of construction. Overcoming the challenges related to nodal connections holds immense promise for revolutionizing the construction industry and opening up new avenues for architectural design and engineering excellence. The ongoing advancements in space grid structures present exciting opportunities for the future of large-scale structural systems.

The design aspects of space grid structures have long been a subject of profound scientific interest and investigation on a global scale. A retrospective analysis of the historical progression of structural development reveals that each innovative architectural form arises from the pursuit of identifying the most economically viable and efficient structural concepts. Extensive research endeavors, spearheaded by scholars, have been dedicated to comprehending and delving into the intricacies of structural designs. These studies predominantly focus on rational design methodologies and the determination of pertinent geometric parameters (Tashakori & Adeli, 2002; Zi & Gan, 2015). In some investigations, significant emphasis is placed on constructive solutions, schematic representations, calculation techniques, and installation methodologies. Moreover, these inquiries delve into the influential role played by the dimensions and configuration of structural elements in shaping the stress-strain distribution and overall mass of the structure.

The academic community (Lan, 1999; De Andrade et al., 2005; Ramaswamy et al., 2002; Gasii & Hasii, 2023), has made notable contributions to the advancement of constructive solutions for space grid structures, as well as the development of precise calculation methods.

Among the critical geometric parameters, depth (h) and module size (a) play a fundamental role in shaping structural designs. The height represents the vertical distance between the upper and lower chord, while the module size corresponds to the span between two joints along the upper chord (Figure 5) (Gasii & Hasii, 2023). Despite their seemingly straightforward nature, the careful selection of suitable values for these parameters can have a significant impact on the cost-effectiveness of the structure. Furthermore, the determination of the height and module size is influenced by various factors, including mesh type, support spacing, roof configuration, and nodal system. Recognizing the interdependence between the height and module size is of paramount importance, and this relationship is governed by the angle (α) formed between the rod of the module and its horizontal projection. Although the optimal range for this angle typically falls between 30° to 60°, a recommended advisory value of 45° is often established to guide the design process.

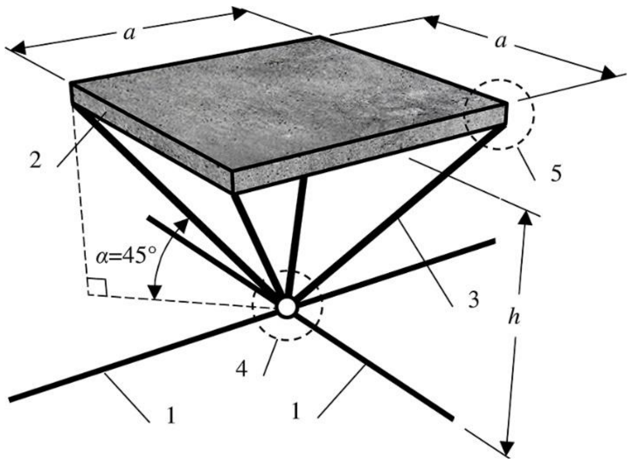


Fig. 5 *Parameters of space grid structures (a space grid unit): 1 – cable or bar; 2 – slab; 3 – web; 4 – connection of top chords; 5 – connection of bottom chords*

The establishment of a standardized ratio between the depth (h) and module size (a) in space grid structures remains elusive and is typically determined based on empirical knowledge. It is widely recognized that these structures tend to have relatively conservative heights compared to traditional counterparts. However, it is crucial to acknowledge that reducing the structural height relative to the span requires the use of smaller module sizes, which in turn increases the number of modules, nodal count, overall structural mass, and cost. Achieving optimal structural design can be accomplished through the application of structural optimization techniques, which help determine the most advantageous height-to-span ratio.

In a specific study (Lan & Qian, 1986), the principles of structural optimization were employed to investigate optimal span ratios ranging from 24 to 72 meters for different height variations in space grid structures. The study encompassed a thorough analysis of seven distinct grid typologies. The module size and height were treated as variable parameters, while the objective function aimed to minimize the cumulative expenditure associated with constituent elements, joints, roofing materials, and enclosure components. This comprehensive approach led to a robust evaluation of the obtained results. The findings revealed significant variations in the optimal design parameters across different structural systems, with the module size generally increasing with the expansion of the span. Additionally, an empirical formulation was derived to determine the optimal proportion between the span and height. Based on these findings, graphical representations illustrating the relationship between the span (L) and depth (h) in space grid structures were meticulously plotted (Figure 6) (Lan & Qian, 1986). Figure 6 also incorporates the results of additional research efforts in this field, as discussed by (Chen & Lui, 2005), providing valuable comparative insights.

In the pursuit of achieving optimal geometric dimensions for modular elements in structural design, significant attention must be given to the development of efficient and reliable constructive solutions for nodal connections. This aspect is of considerable importance in ensuring the overall performance and integrity of the structure.

In the field of structural design, engineers face the intricate challenge of seamlessly incorporating rod elements with varied cross sections. The successful integration of these elements relies on the skillful implementation of nodal connections at the precise junctions where they converge. This field represents a fusion of innovation and creativity, serving as the foundation for the construction of extraordinary structures.

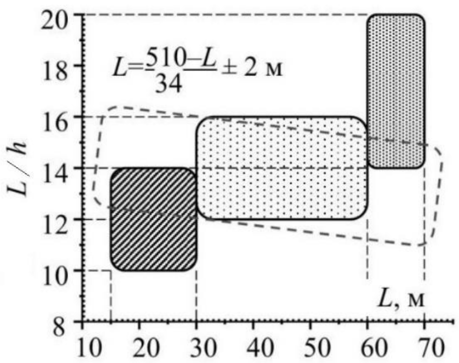


Fig. 6 *Dependencies between parameters*

Within this trend, a multitude of solutions for nodal connections has emerged, each offering a unique approach with its accompanying characteristics as well as advantages and disadvantages. These designs according to different reasons can be categorized into distinct groups, each possessing its own merits and drawbacks. According to the nature of the behaviour designs are categorized into three distinct groups (pinned or hinged nodal connections; rigid nodal connections; semi-rigid nodal connections), and according to the manufacturing method designs are categorized into three distinct groups also.

Group I comprises nodal connections achieved through the skilled technique of welding during the assembly phase. Welded joints have the remarkable ability to join rods together at various angles and in different quantities. They offer potential flexibility and adaptability in the field of structural design. However, these joints also present significant challenges. Strict welding requirements, precise alignment of angles to mitigate eccentricity, and the absence of easy disassembly and reassembly of components pose formidable obstacles. Additionally, welding introduces stresses and non-uniformity into the structure, necessitating adherence to prescribed rod length requirements. As a result, welded node connections have not yet gained widespread acceptance. Notable examples in this category include the Oktaplatte system, Segmo, and SDC, each contributing to the ever-evolving area of nodal connections.

Group II, in stark contrast, embodies an alternative approach, relying on bolted connections and modular components, thereby eliminating the need for welding. This alternative method opens up a realm of possibilities, allowing engineers the freedom to assemble and disassemble elements without the constraints imposed by welding. Bolted connections can be further categorized based on the functionality of the bolts, whether operating under compression, tension, or as shear-resistant elements. The versatility and convenience offered by this approach have resulted in a wide range of bolted node connection systems. Engineers have embraced the flexibility and simplicity of the bolted connections to bring designs, including the Sarton system, Premit, Triodetic, Mero, and many others.

Group III represents a hybrid approach that combines the strengths of both ways —factory welding and on-site assembly using bolts. This innovative combination enables the efficient fabrication of nodes by utilizing specialized connector components made from various materials such as cast, forged, or welded spheres, hemispheres, and polyhedrons. The integration of welding and bolts in this approach provides engineers with a powerful tool to achieve both structural robustness and adaptability in their designs. It exemplifies a harmonious collaboration between precision manufacturing and on-site construction. The possibilities within this group are extensive, offering a link between the resilience of welded joints and the versatility of bolted connections.

As we delve into the captivating world of nodal connections, we encounter remarkable examples that showcase the ingenuity and expertise of structural designers. Among these examples, the Oktaplatte system stands out as an iconic solution in the realm of welded node connections, reflecting the engineering prowess of Germany. This innovative system consists of two hemispherical hollow steel parts connected by a steel diaphragm in the form of a disc, combining strength and elegance. Its notable application can be witnessed in the construction of the pavilion for the World New York Exhibition, an architectural marvel that captivated global attention from 1964 to 1965.

In contrast, bolted node connections encompass a wide range of systems, each characterized by unique features and advantages. From the Sarton system to Envision, Unibat, Nodus, and many more, engineers have embraced the versatility and reliability offered by bolted connections to bring their structural visions to fruition.

Within the ever-evolving realm of structural design, nodal connections play a pivotal role as crucial junctions that seamlessly unite rod elements with diverse cross-sections. These connections not only provide structural integrity to the overall system but also enable the realization of awe-inspiring architectural achievements.

In the field of structural design, engineers and designers constantly explore new avenues and employ cutting-edge techniques in their quest for optimal nodal connections. This pursuit aims to uncover ground-breaking solutions that enhance efficiency and functionality.

With each passing day, the evolution of nodal connections unveils new possibilities, inspiring future generations of structural designers. It represents a compelling narrative of ingenuity, where the fusion of art and engineering brings towering structures to life, defying the laws of gravity.

The discovery of nodal connections continues, driven by technological advancements and the emergence of novel materials. These advancements propel the field of structural design forward, offering increasingly sophisticated and efficient solutions. They stand as a testament to human creativity and the unwavering pursuit of excellence, resulting in the construction of enduring structures that withstand the test of time.

Let us now embark on this captivating narrative, where the seamless integration of rod elements and the art of nodal connections unite, shaping the world around us and leaving a lasting legacy for generations to come. Together, we can redefine the boundaries of structural design, explore new horizons, and create structures that epitomize the brilliance of human achievement.

A comprehensive investigation into bolted nodal systems worldwide has unveiled a diverse array of proprietary systems, each showcasing distinct structural attributes concerning connection methods for rod elements, cross-sectional shapes, and connector core element configurations.

In the realm of space grid structures, nodal connections utilizing axial bolts have gained significant recognition. Among these systems, the Mero system, originally conceived by German designer M. Mengeringhausen, holds a prominent position. This system employs a solid steel spherical polyhedron connector with threaded holes, enabling the connection of up to 18 rod-shaped elements using axle bolts and sleeves. The Mero system has undergone several modifications and advancements over time (Stephan et al., 2004; MERO-TSK, n.d.) (Figure 7).

(a) **(b)**

Fig. 7 *Third canopy structure in Chile - Hospital Penco-Lirquen (a) and Lutz in Kempten, Germany (b)*

Similar systems, such as Orona, Cubotto, Vestrut, and Villeroy, have also been developed, featuring multi-component connectors secured by a central bolt.

A thorough examination of well-established nodal connections reveals that the majority of them utilize bolts specifically designed for connecting elements with tubular sections. In most cases, these nodal connections subject the bolts to significant axial tension or compression forces. However, assembly errors, accidental damage, or deformation can introduce bending moments that pose a risk to the integrity of bolts in the non-threaded region. In (Gasii & Hasii, 2023), a proposal is presented for designing nodal connections in space grid structures involving tubular elements, aiming to mitigate the potential for bolt failure under bending loads. The proposed design highlights the versatility of the connection, making it suitable for various building and structural applications, including arches, domes, and stadium roofs. Studies demonstrate that the developed node exhibits superior performance by utilizing standard bolts capable of double cross shear, resulting in up to about a 2.5 times increase in load-bearing capacity compared to specialized bolts used in the Mero system.

Taking into account the specific characteristics of existing nodal connections in space grid structures and insights from research, nodal connections employing welded sheets emerge as the most efficient option in terms of ease of assembly. These constructive solutions simplify the shape of the nodes, leading to reduced production costs. Furthermore, nodes consisting of single solid parts, whether stamped, milled, or bent, offer reduced complexity and enhanced reliability by eliminating the potential weakening effects associated with welds.

The cost of space grid structures is significantly influenced by the complexity level of nodal connections, thereby impacting their technical and economic feasibility. Nodal connections contribute to approximately 20% of the total steel usage in these structures. Without exception, all space grid structures are composed of rods and junctions, and the combined mass of these bars and nodal elements determine the overall weight of the structure. The total weight of the modular cell within space grid structures is obtained by multiplying the construction ratio of space grid structures by the weight of the rods (Figure 8) (Khisamov, 1981). Furthermore, the weight of the rods, which varies depending on the type of lattice structure, is determined using distinct formulas. The aforementioned study also provides graphical representations of construction rations calculated for the most commonly used nodal solutions, with their values based on the span of the structures. These graphs facilitate the identification of suitable geometric parameters for a specific type of nodal connection. For example, for large spans exceeding 40m, the Mero, Unistrut, and KIBI systems are not considered rational nodal connection systems due to their substantial increase in construction rations compared to flat trusses.

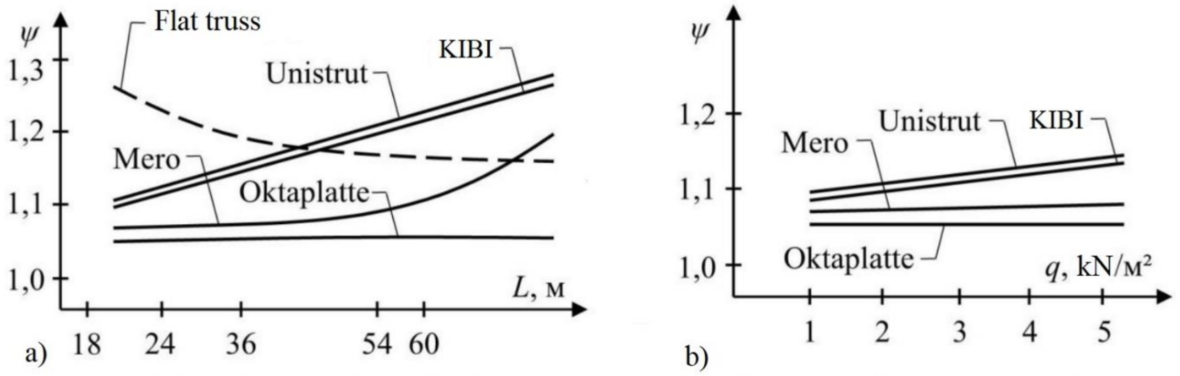


Fig. 8 *Dependence of the construction ratio ψ on span (a) and loading (b)*

Nodal connections possess not only weight but also pliability, which significantly influences the stress-strain behavior of structures (Estrin et al., 2021). In space grid structures characterized by a high degree of redundancy, the pliability of nodal connections deviates the structures from their intended behavior, leading to stress redistribution. Moreover, in space grid structures that incorporate elements with varying bolt accuracy, the pliability of bolted connections becomes a crucial factor as it contributes to increased structural deflection (Gasii et al., 2020, 2022). In such scenarios, it is advisable to augment the total deflection obtained for a system with fixed connections by 30% when the difference between the bolt diameter and the whole diameter is between 2-3mm, and by 20% when the difference is 1.5mm. Furthermore, the pliability of nodal connections exhibits different degrees and types of influence on the behavior of space grid structures, contingent upon their specific type. For instance, accounting for the pliability of nodal connections in a mesh dome has resulted in stress reductions of up to 15% in rod elements. However, the impact of pliability in space grid slabs varies. Observations indicate that stress redistribution in space grid slabs is highly non-uniform: the pliability of bolt connections induces minor changes in some elements, while in others, stress variations can range from 20% to 60%, and in certain cases, even change signs. Consequently, it is imperative to consider the calculation of structures with bolted connections, taking into account the potential pliability, to achieve an accurate behavioral representation.

The pliability of nodal connections can be effectively addressed through various methodologies, which aim to enhance structural deformability. One approach involves substituting the elastic modulus of the nodal connections, allowing for a more accurate representation of their pliable behavior. Another strategy entails incorporating elastic elements at the extremities of the rods, which introduces flexibility and helps accommodate deformations. Additionally, nodal connections can be modeled as polygons, considering their inherent pliability within the structural analysis. Implementing any of these methods to account for the pliability of nodal connections results in increased deformability of the structure.

Furthermore, it is essential to emphasize the importance of maintaining overall integrity and reliability when selecting node connections and components for space grid structures. Design errors can lead to excessive material consumption, complexities during erection, suboptimal operational efficiency, and undesirable initial stresses. Therefore, it becomes crucial for the load-bearing capacity of nodal connections to exceed that of the most heavily loaded rod member in tension, ensuring sufficient reserve load-bearing capacity for the entire structure. Adhering to this principle ensures that even in the unlikely event of an accidental failure of the most highly stressed element or node, the situation remains non-critical due to stress redistribution mechanisms. Conversely, if the design exhibits an inequality where the load-bearing capacity of the most stressed member surpasses that of the node, indicating an excess of steel, the imbalance must be rectified. Consequently, the selection of nodal connections necessitates a comprehensive analysis encompassing all relevant aspects to facilitate well-informed decision-making.

The analysis of research findings and exploration of strategies to enhance nodal connections in space grid structures have yielded significant insights into their design and construction. It has been established that the complexity of the connection node plays a critical role in determining the erection cost of these structures. The load-bearing capacity of space grid structures is intricately linked to the strength of the node, and nodes designed with excessive strength reserves often result in an unnecessary surplus of steel. Consequently, simpler node designs that facilitate easier manufacturing and assembly process not only save time but also reduce steel consumption. The decreased labor and material requirements contribute positively to the overall cost reduction of the structure.

Nodal connections in space grid structures can be categorized as bolted, welded, or combined, with bolted connections being widely utilized due to their prefabricated nature and efficient assembly procedures. However, it is important to acknowledge that welded joints can be equally effective. For example, the use of lap joints instead of butt joints during component assembly can reduce the accuracy requirements for rod lengths. Additionally, in welded assemblies subjected to light loads, steel rods with round or square cross-sections can be employed as lattice members.

Building upon the gathered information, several approaches have been proposed to enhance space grid structures, leading to the development of a novel concept known as the steel and concrete composite cable space frame (Gasii, 2019) (Figure 9 and Figure 10). Details of the calculation and construction of that system are considered in the manuscript (Gasii & Hasii, 2023)

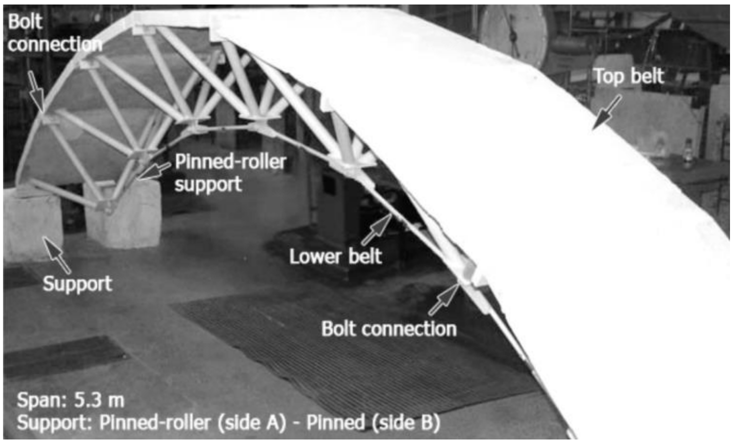


Fig. 9 *Example of the novel concept of the space rod system (the steel and concrete composite cable space frame) (Gasii, 2019)*

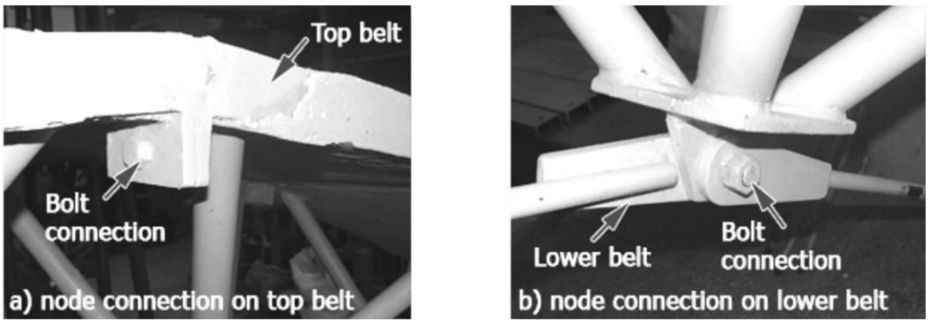


Fig. 10 *Node connections of the steel and concrete composite cable space frame (Gasii, 2019)*

This system offers unique features by enabling collaboration between grid modular elements and durable building materials, including translucent options. Structurally, these systems consist of top and bottom cords combined with a space lattice. The top chord comprises rigid plates capable of withstanding compression and transverse forces, while the bottom chord consists of flexible linear elements (Gasii, 2019; Gasii et al., 2020, 2022; Gasii & Hasii, 2023). It is important to note that this structure is modular (consists of space grid units), with space structural modules being fully fabricated within a controlled factory environment. Three types of modules are present within these systems: support and span space modules, as well as line modules used to form a flexible chord. This structural concept allows for the construction of covers with various forms and shapes, including different shell configurations (Gasii & Hasii, 2023). Specially designed nodes are employed to connect the modules into a cohesive structure. Theoretical, numerical, and experimental investigations conducted on this system demonstrate its efficiency, reliability, and potential for resource conservation, making it particularly relevant in the contemporary construction industry.

4. Conclusion

Considering the factors discussed above, the importance of nodal connections in structures becomes evident, as they directly affect material usage and installation complexity in space grid structures. These connections can be categorized into three types: bolted, welded, and combined. Among these, combined connections are commonly preferred in practical applications. It should be noted that many existing connection nodes, including those employing welded techniques, rely on specialized steel fasteners, which add weight and increase the complexity of assembly, necessitating precise component fabrication.

A thorough analysis of both theoretical and experimental studies has revealed that combined connections incorporating gussets offer the most efficient nodal configuration. This is due to their ease of production, lightweight nature, and absence of axial bolts. However, it is important to acknowledge that these nodes also have certain limitations. They require a significant number of bolts and present challenges when incorporating tubular rod elements. Additionally, in the case of welded connections, the overall length of the welded assembly becomes substantial. Consequently, while theoretical investigations have presented promising nodal configurations, there are still unresolved issues that require further exploration and analysis.

Therefore, a novel concept for a space grid system has been developed, introducing a structural solution that optimizes material usage and human resources during the construction of covers with diverse forms and shapes for large-span buildings. This innovative approach aims to enhance efficiency and address the challenges associated with nodal connections in space grid structures.

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