

Review

## Advancements and applications of lightweight structures: a comprehensive review

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### Abstract

Lightweight structures comprise of actual pieces or segments that give the crucial ability to function while weighing less than other possibilities as well. The aerospace industry invented this particular branch of expertise, which is sometimes referred to as lightweight engineering or lightweight construction. This paper focuses on how lightweight structures are developed and applied in the field of structural engineering which is essential to achieving the high standards and breakthroughs of modern science. Comparison is made depending on different types of lightweight materials such as titanium alloys, shape memory alloys, magnesium, aluminum alloys, and wood composites, benefits, and applications of each type of material are discussed. Recent technologies and innovations in the field of lightweight design are performed including deployable and morphing structures, 3D printing, embedded sensors and actuators, and advanced joining technologies. Moreover, research is also being done on these structure types of evolution, uses, and significance, as well as their design techniques and innovations. Truss, tensegrity, pantographic, cable, origami, and sandwich structures are identified by explaining their properties and working mechanisms. The usage of several lightweight structures in the fields of aerospace, robotics, civil engineering, architecture, automotive, and biomedicine is examined in this paper. Additionally, the comparison is made between the application of tensegrity, truss, pantographic, and sandwich structures in aircraft applications in detail, while the importance of shape morphing and deploying of pantographic and origami structures is explained in the field of aerospace and robotics. In addition, different types of bridge structures and architecture are mentioned according to applications of suspension cables, stayed cables truss structures, and tensegrity techniques. Furthermore, the paper covers the improvement of computational and numerical techniques in the analysis and design of lightweight structures including the force method, dynamic relaxation method, and finite element method (FEM), trends in optimization techniques and their applications are included mentioned sequential quadratic programming (SQP) and interior point optimization, with applications on different types of lightweight structures. Also, perspectives and future directions of lightweight design through sustainability and smart construction are taken into account, importance of lightweight design in the form of environment and innovation is clearly supported.

**Keywords** Lightweight structures · Structural engineering · Materials · Analysis · Design · Applications · Challenges

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## 1 Introduction

Lightweight structures are made up of physical elements or sections that provide the necessary technological capabilities while weighing less than alternative solutions. Less material, greater functionality, and lighter construction can all help achieve this [1]. Lightweight design aims to reduce structural weight while maintaining requirements of durability and dependability through the interdisciplinary area of lightweight engineering, which integrates computer technology, material science, manufacturing, and materials mechanics. Increased productivity with the least amount of resource use is the aim of lightweight design [2]. Such structures are increasingly widespread due to their environmental and structural benefits [3] and their positive response in life cycle assessments [4]. Lightweight buildings are one of the most popular architectural types in design and construction today. What catches our attention about them is their unique design and creative solutions. From the perspective of form discovery, architects and designers find the idea of lightweight structures to be highly enticing [5].

This particular field of study, known as lightweight engineering or lightweight construction, was created by the aircraft industry. It is especially important when engineers deal with dynamic structures. An airplane, for instance, cannot be constructed or designed without careful consideration of lightweight materials. But there are other technical fields, including structural, mechanical, automotive, and rail vehicle building, that also have lightweight construction problems that need to be solved [6]. The goal of research and development in the discipline of producing mechanical equipment is to determine ways to balance component performance (such as strength or flexibility) with stiffness rather than dropping weight [2]. Lightweight technology is the best method to deal with this problem [7]. Lighter equipment can perform better, as in the case of a faster-accelerating car or jet or sports equipment that gives an advantage over a competitor. Because lighter items require less energy to function in many applications, they also have reduced life cycle costs [1].

Structural engineers divide the design process into three primary stages. The first step is to determine what the structure requires. Second, give one or more structural perceptions that satisfy the given requirements. Third, assess and put the proposed idea to the test [8]. The building industry must change. The majority of structures today are not effective or sustainable. Multiple materials make up stiff and immobile objects, yet their external environment is ever-changing due to factors including time, location, loading type, and level. Reducing the need for structural materials and increasing efficiency are two benefits of adapting buildings to changing environmental circumstances [9]. Because of their versatility and efficiency in use, lightweight buildings have the benefit of being able to serve as a foundation for more flexible structures. Adaptive structures have the ability to actively change their form and internal load channels in response to external forces. According to, these structures consist of actuators, control intelligence, and sensors [10]. Adaptive and morphing structures are increasingly prevalent in many engineering domains. There aren't many acknowledged practical uses for civil engineering at the moment. Novel structural ideas, such as morphing, inflatable, and deployable structures, could offer new approaches to issues confronting the building industry [11]. Structures used to support delicate scientific, or communications equipment may be placed in challenging conditions, like space, or require complicated structural performance. These structures frequently resemble pin-jointed assemblies or have pin-jointed assembly-like characteristics [12].

The concept of lightweight structures originated after the nineteenth century when new materials and production methods brought about by the industrial revolution freed architecture from the load-bearing wall [13]. The American high-rises designed by Walter Gropius and Mis van der Rohe in the 1920s and Paxton's Crystal Palace (1851), which was built using glass and iron to save weight, are early instances of this transition [11]. Technological developments and space exploration have greatly improved structural conceptions and designs. In space, gravity—the primary weight of large buildings on Earth—drops substantially to a fraction of solar pressure. Large spacecraft structural designers had to find innovative designs that could withstand the rigors and conditions of space voyages [8]. These days, scientists are trying to expand the ability of these assemblies to meet technological needs in a range of applications. In order to explore new approaches to analysis and design based on developing trends in computer analysis, mathematical research, and physical applications, a number of studies were carried out. These challenges led to the creation of intelligent structures based on these assemblies. Using optimization to design lightweight buildings is a significant advancement made possible by a number of processes and is essential to the long-term development of modern technology and building designs. For example, using optimization techniques by altering stress controlling mechanism [14], to minimize the weight of truss structures [15] and get the maximum stiffness-to-mass ratio while adhering to the intrinsic frequency constraint for large-scale deployable antennas [16]. In applications where

structural tolerance is critical, it is vital to reshape distorted structures under stress [17]. For example, Mitsugi et al. [18] stated that changing the length of the cables in a tension truss antenna can change its surface form, and it can also improve certain surface deformations without changing the overall surface geometry. Many challenges to using different types of lightweight structures in aerospace engineering were recorded, such as using pantographic structures in aerofoil sections by Saeed and Kwan [19], Chiral truss core aerofoils by Spadoni and Ruzzene [20], and using composite lattice-based cellular structures for active wing shaping concept by Jenett et al. [21]. There are great explorations to applying lightweight structures in improved robotic fields that can be used to serve humanity for example, pantograph based wall climbing robot by Ariga et al. [22] and a portable inspection robotic device that evaluates the condition of railway pantographs using passive movement and structural dynamic excitation by Santamato et al. [23].

The advances and applications of lightweight structures in the field of structural engineering are the primary subjects of this research. Numerous lightweight structure types are the subject of research, which is essential to achieving the high standards and breakthroughs of modern science. Research is also being done on these structure types of evolution, uses, and significance, as well as their design techniques and innovations. This study's outline covers the following topics: advancements in analysis and design methods, such as computational methods and finite element analysis (FEA), applications of various lightweight structures in the aerospace industry, robotics, civil engineering, and architecture, automotive, and biomedicine; challenges in lightweight design and future trends; and improvements in materials and technologies in the field.

## 1.1 Lightweight materials

Applications for structural lightweight materials are numerous, and they are crucial to the advancement of lightweight technologies and structures. Due to the necessity to decrease the weight of cars and airplanes, increase energy efficiency, and meet strict functional criteria, the aerospace and automotive sectors have long been at the forefront of the development of novel structural lightweight materials. Blanco et al. [24] looked at and evaluated scientific literature from 2000 to 2020, with an emphasis on lightweight structural materials and multi-materials with prospective applications. The primary materials focused on by Blanco et al. [24] were aluminum alloys, titanium alloys, fiber-reinforced polymers, and magnesium. Apart from these materials, shape memory alloys, high-strength steel, ceramic matrix composites (CMC), and wood composites are discussed in this section. The background, important, composition, properties, and applications of each material are mentioned in detail.

### 1.1.1 Aluminium alloys

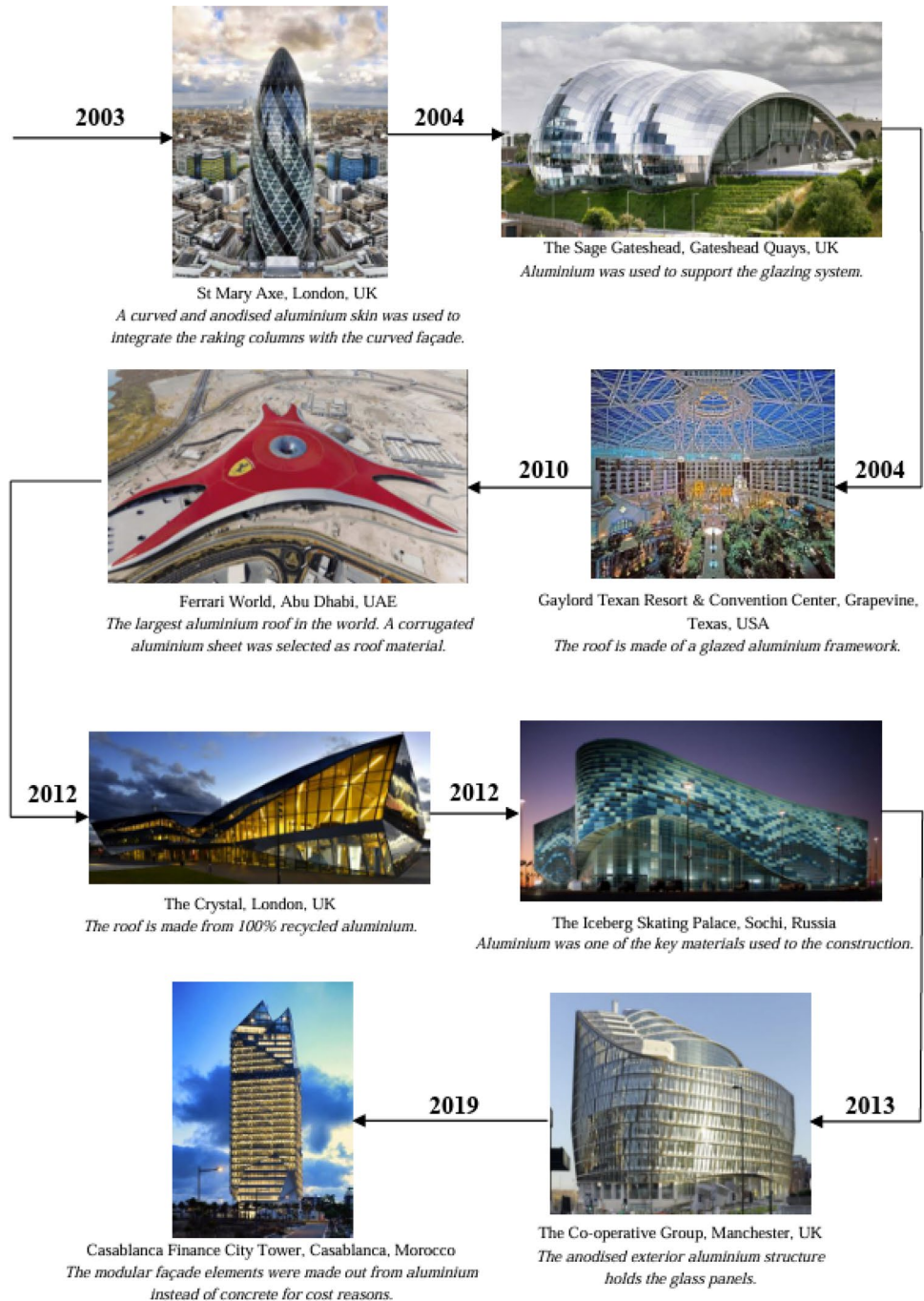
The third most common metal in the crust of the planet is aluminum. Aluminum's formability, attractiveness, particular strength, low weight, and corrosion resistance are its distinguishing qualities. While certain aluminum alloys, such as AA7075, are known for their superior strength over structural steel, pure aluminum, and various aluminum compounds are known for their low strength and hardness. According to ASM-Committee [25], at low temperatures, the majority of aluminum alloys retain their strength and ductility, and some even noticeably improve them. Çam and İpekoğlu [26] provided a summary of the advancements made in the joining of aluminum alloys in recent years, along with recommendations for the industry and researchers working in this area and on the heat-treatable aluminum alloys' weldability found that these alloys can be effectively connected using low heat input arc welding techniques such cold metal transfer arc welding or pulsed arc welding. It is also well acknowledged in the same research that friction stir welding (FSW) has significantly more potential than fusion welding when it comes to joining Al alloys. For instance, FSW does not necessarily lead to a loss in joint area strength in solid-solution-hardened Al alloys.

In aluminum alloys, lithium is the most lightweight alloying ingredient. Aluminum alloys gain strength and reduce weight when lithium (Li) is added. Specific strength (strength/density) and stiffness are significantly increased by combinations of synergistic properties. Beryllium (Be) and Lithium (Li) are the two elements that may reduce density while significantly raising the Young's modulus of aluminum alloys [27]. Noble et al. [28] stated that lithium may be dissolved in aluminum up to 14% (4 weight percent) and, with the correct heat treatment, this can lead to Young's modulus of up to 86 GPa, which is 30% more than pure aluminum. Moreover, a study by Meric [29] aimed to determine the density and elastic modulus of aluminum alloys (2024 + LiX) and concluded that for every 1% increase in additional lithium, there was a 6% increase in the modulus of elasticity and there was a 3% drop in alloy density for every 1% increase in additional lithium. The same research stated that Al-Li alloys were produced in a safer manner than any other traditional technique.

Aluminum alloys are increasingly employed as structural materials as shown in Fig. 1. It is due to their desirable features, which include a high strength-to-weight ratio, ease of fabrication, workability, ductility, superior thermal conductivity, corrosion resistance, and an appealing natural finish [30].

The remarkable qualities of aluminum matrix composites (AMCs) include high strength and modulus of elasticity, ductility, strong wear and corrosion resistance, high creep temperature, good fatigue performance, and low coefficient of expansion. They are extensively utilized in robotics, high-speed machinery, rotating shafts, car engines, and braking systems in the automotive and aerospace sectors. The microstructure of the reinforcing matrix needs to be uniform, with ceramic particles dispersed uniformly throughout [24].

**Fig. 1** Examples of aluminum alloy structures [30]



## 1.2 Titanium alloys

Titanium alloys are often used in engineering, especially in the aerospace and automotive sectors [31]. Titanium and its alloys are frequently employed in aircraft, due to its high specific strength (weight-to-strength ratio) at high temperatures and resilience to corrosion and fracture [32, 33].

Titanium is available both commercially pure and as an alloy. These alloys are often divided into three types: alpha, alpha–beta, and beta [34]. The components of commercially pure titanium include elemental titanium plus impurities including iron, nitrogen, hydrogen, and oxygen. There are several different grades of commercially pure titanium materials and stronger elements are those that contain more O and Fe [34, 35]. While Alpha alloys are formed from a single solid solution. Although these alloys have excellent high-temperature properties, heat treatment cannot improve their microstructure [34, 36]. Among the most versatile titanium alloys are beta alloys. These titanium alloys are the best for aeronautical applications because they have the highest strength-to-weight ratios and profound hardenability [37]. However, as Evans [38] discussed, alpha–beta titanium alloys will require more efficiently use if they are to meet the performance demands of the next century. This would only be feasible with a fuller understanding of how the alloys fracture and deform under conditions of cyclic stress.

Zhu et al. [39] explained that titanium alloys are superior to other metals in many aspects because of their high specific strength, high stiffness, amazing fatigue resistance, exceptional fracture toughness, exceptionally strong heat resistance, cryogenic embrittlement resistance, and low thermal expansion. Titanium alloys are an excellent alternative to steel and aluminum alloys in engine and airframe applications because of their advantages. Unfortunately, the high cost (about eight times more than commercial aluminum alloys) and poor manufacturability of titanium alloys restrict their widespread use.

## 1.3 Fiber reinforced polymer

Fiber-reinforced polymers (FRPs) offer lightweight and structural properties such as rigidity, mechanical strength, and corrosion resistance. The three most important families of FRPs are carbon fiber-reinforced polymer (CFRP), glass fiber-reinforced polymer (GFRP), and fiber metal laminates (FML). The fibers provide strength, stiffness, and lightweight, while the matrix provides structural integrity and load-bearing capacity. FRPs exhibit global anisotropy and brittleness, making machining challenging. The mechanical properties of a composite material are influenced by the fibers' orientation and stacking, for example, depending on the orientation of the fiber, the direction of the fiber produced the most strength, whereas the direction perpendicular to it produced the lowest strength [24, 40].

There are investigations of this type of material with applications in the field of lightweight design. Bačinskas et al. [41] conducted an experimental study to examine the structural behavior of a glass fiber-reinforced polymer (GFRP) space truss bridge model under static loads. Steel bolts, GFRP brackets, and Fiberline Composites, GFRP profiles were used in the assembly of the bridge prototype. The wooden bridge deck was erected to support the weight of the building. The insights gained show that there was a sufficient reserve of structural stiffness in the bridge model, which was constructed and tested. A situational investigation reveals that GFRP profiles perform well on real pedestrian bridge superstructures. Also, to create a standard truss panel, a GFRP-steel combination truss is proposed by Liu et al. [42]. The study shows that the node of a completed truss panel is built in a convenient, reliable, and safe manner; the design of the rods' creep control feature guarantees that, in addition to satisfying the design requirement for short-term structural stiffness, the long-term creep deformation tends towards stability. Moreover, there are no appreciable alterations in the elastic modules, suggesting that this structure might find application in practical engineering.

Moreover, carbon fiber reinforced polymers (CFRP), are widely utilized in the construction of Airbus aircraft because they are stronger, lighter, and more resistant to corrosion than metal. They also considerably increase fuel economy [24]. Also, other characteristics of CFRPs include low density, high stiffness-to-mass ratio, improved fatigue and wear resistance, superior dimensional stability, low coefficients of friction, expansion, and electrical conductivity [43]. Furthermore, Zhang et al. [44] suggested a design approach to connect conceptual and detailed design and optimize the composite of the automotive floor made of carbon fiber reinforced polymer (CFRP) by combining free size optimization and size optimization methods. The goals are to increase the lightweight level of the automotive floor, lower the cost of material application, and improve integrated process manufacturing performance through structural design and optimization.

Further details on creating new machinery to raise the adaptability and caliber of FRP manufacturing processes are provided. Applications involving aircraft skin and fuselage currently make use of automated tape laying (ATL) and automated fiber placement (AFP). Robots are being employed more and more to reduce equipment size and increase industrial flexibility. Because AFP heads are deeply ingrained in machinery [24]. Figure 2 Automobile components made of natural fiber composites [45, 46].

#### 1.4 Magnesium

One metal that has multiple useful applications is magnesium. It is made from seawater which is 98.8% pure and makes up 2.7% of the earth's crust. It is a suitable replacement because of its density, which is 25% that of steel and 66% that of aluminum. Although magnesium is the lightest structural alloy in the world, when the thickness of pure laminated polycrystalline magnesium is lowered by around 30%, fractures and cracks start to show. Although alloying materials may improve this, no super-formable magnesium alloy has been developed at ambient temperature [24]. Instead of using iron and aluminum, magnesium alloys are frequently used as lightweight structural components. These days, magnesium alloys are employed in a multitude of products, such as cell phones, laptop computers, and automobile parts. The alloys' increased strength and heat resistance increases the range of possible uses. The purpose of using magnesium alloys as structural materials for automobiles is to lower energy consumption and promote the growth of new industries [47].

#### 1.5 Shape memory alloys

Shape memory alloys (SMAs) exhibit unique characteristics such as pseudoelasticity, which allows them to resist massive deformations that may be recovered after unloading, and shape memory effect, which allows them to revert to their prior shape when heated above critical temperatures. SMAs function as actuators in numerous situations [48]. The memory effect's form was initially observed in 1930. The Swedish researcher Arne Olander discovered that these phenomena might be caused by gold-cadmium alloys and the pseudoelastic property of this alloy is explored. Also, the shape memory effect has been seen in materials like the copper–aluminum–nickel alloy since the 1950s. Moreover, there are investigations of nitinol (Ni–Ti), a NiTi alloy. The US Naval Ordnance Laboratory made the initial discovery of nitinol alloy [49]. NiTi shape memory alloys (SMAs) are a well-known metal-based material distinguished from more traditional damping materials like polymers and composites by their exceptional super elasticity and distinct shape memory effect [50, 51]. Aerospace engineering uses shape memory alloys for a number of purposes, including the ability to transform aircraft. Designers must construct innovative configurations to maximize the integration and performance of SMAs that function as actuators by using the shape memory effect and absorbing structural stresses [52].

#### 1.6 High strength steel

It has long been wanted to produce improved steels with high strength, ductility, and toughness. Dual-phase steels, transformation-induced plasticity (TRIP) steels, and high manganese austenitic steels intended for automotive applications are examples of advanced high-strength steels. The necessity to further reduce vehicle weight has given rise to another notion of advanced steel in recent years [53]. It is vital to take into account the interplay of service loads, materials,

**Fig. 2** Automobile components made of natural fiber composites [45, 46]



material characteristics, geometry, and manufacturing procedure in order to effectively employ high-strength steel for lightweight structural design. When it comes to steel-based buildings, decreasing thickness can always lead to a large weight reduction; nevertheless, in order to keep the same stiffness, the outside dimensions must be increased [54]. It is well-acknowledged around the world that traditional building materials material used in automobiles. High-strength steel has a greater yield and failure strength than mild steel. High-strength steel sheets can minimize plastic deformation and increase impact energy absorption in car bodywork. To reduce vehicle weight, body portions should be made of lower-depth, high-strength steel sheets rather than mild steel. During a collision, the plastic deformation of the front body may absorb a large amount of energy. These stampings may shatter due to plastic hinges or stretching. The use of high-yield strength steel sheets in place of mild steel sheets allows for the reduction of body part thickness while retaining the same impact energy absorption capabilities, resulting in a lighter vehicle [55]. Over the last 25 years, many high-strength steels have been developed. AHS steels, as opposed to conventional high-strength steels (HS), are multiphase and have uncommon mechanical properties due to the presence of martensite, bainite, and residual austenite. High manganese steels (HM) are austenitic steels with a high manganese content, ideal for automotive applications [56]. Types of different (HSS) are shown in Table 1.

### 1.7 Ceramic matrix composites (CMC)

Ceramic fibers incorporated in a ceramic matrix are known as Ceramic Matrix Composites (CMC). Both oxide and non-oxide ceramic materials make up the fibers and matrix. It is possible to tailor the qualities of CMC to certain building functions. They are especially appropriate for parts that need to function well both mechanically and thermally [57]. Dhanasekar et al. [58] stated that ceramic matrix composite materials are employed in a variety of aerospace components, including engines, brake disks, and gas turbines due to their unique qualities such as high tensile strength at high temperatures, exceptional corrosion resistance, high hardness, erosion resistance, low density, and strong elastic modulus. Zivic et al. [59] high temperatures during the production and service of CMC components need matrix-reinforcement combinations that consider temperature resistance, chemical compatibility, and thermal expansion mismatches. In addition, Chan et al. [60] explained that, while CMCs have a variety of applications, researchers have encountered obstacles including as brittleness, restricted electrical conductivity, and low thermal characteristics. Despite the exceptional mechanical properties of oxide and non-oxide ceramics as well as ceramic matrix composites, such as their strength and hardness, their large crystals and microstructures can lead to stiff fractures, pitting, and nicks, which reduces their dynamic strength [61].

### 1.8 Wood composites

Wood composites are wood-based manufactured goods made of a range of wood species and non-wood lignocellulosic components. They are joined using artificial or organic bio-based glue solutions and are made to fulfill certain performance and value-added application requirements [62, 63]. It is well acknowledged around the world that traditional building materials and commodities may be enhanced in value by utilizing wood-based composite technology. This kind of economic and material growth scenario may also help producers by enabling them to use and adjust to the constantly

**Table 1** High-strength steel (HS), advanced high-strength steel (AHS) and high manganese steel (HM) types [56]

HS steels	BH	Bake hardening
	IFHS	High strength IF
	P	Rephosphorised
	IS	Isotropic
	Cmn	Carbon/manganese
	HSLA	High strength low alloyed
	AHS steels	DP
TRIP		Transformation induced plasticity
CP		Complex phase
PM		Partly martensite
HM steels	HMS	TRIP high MN transformation induced plasticity
	HMS	TWIP high MN twinning induced plasticity

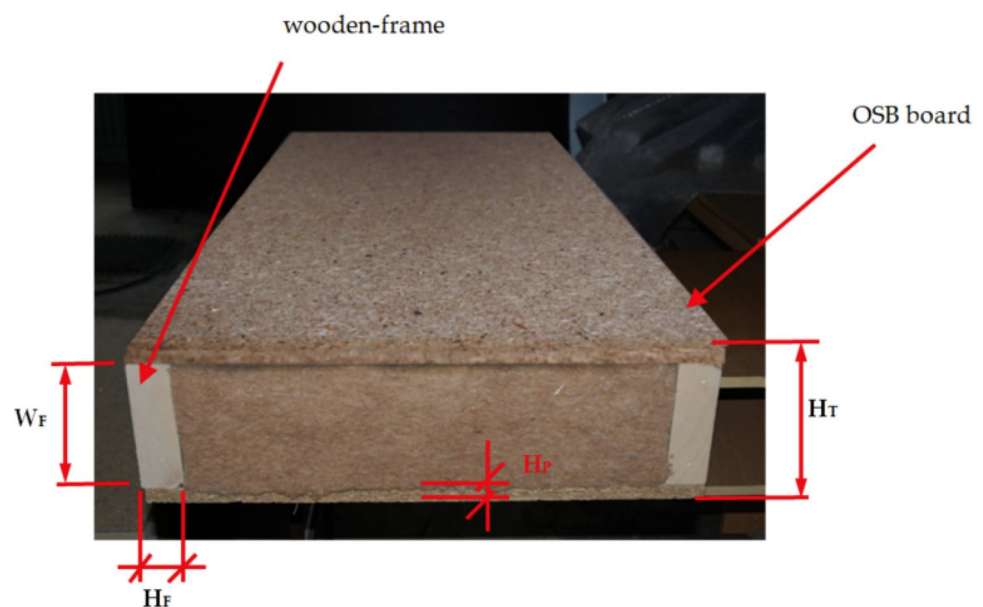
changing quality level of wood through the development of industrial composite processing technologies [64]. Timber structures are gaining appeal due to their advantages in construction procedures, lower life cycle costs, and energy savings, particularly in mid-rise buildings [65]. Szczepanski et al. [66] stated that Wood and wood-based products offer better mechanical properties and contribute to reduced CO<sub>2</sub> emissions than concrete structures and mentioned practical examples of wood composite structures which consist of a frame made of sawn timber and an oriented standard boards (OSB) casing, with the center filled with thermal insulation material as shown in Fig. 3.

## 2 Technologies in lightweight structures

### 2.1 Deployable and morphing structures

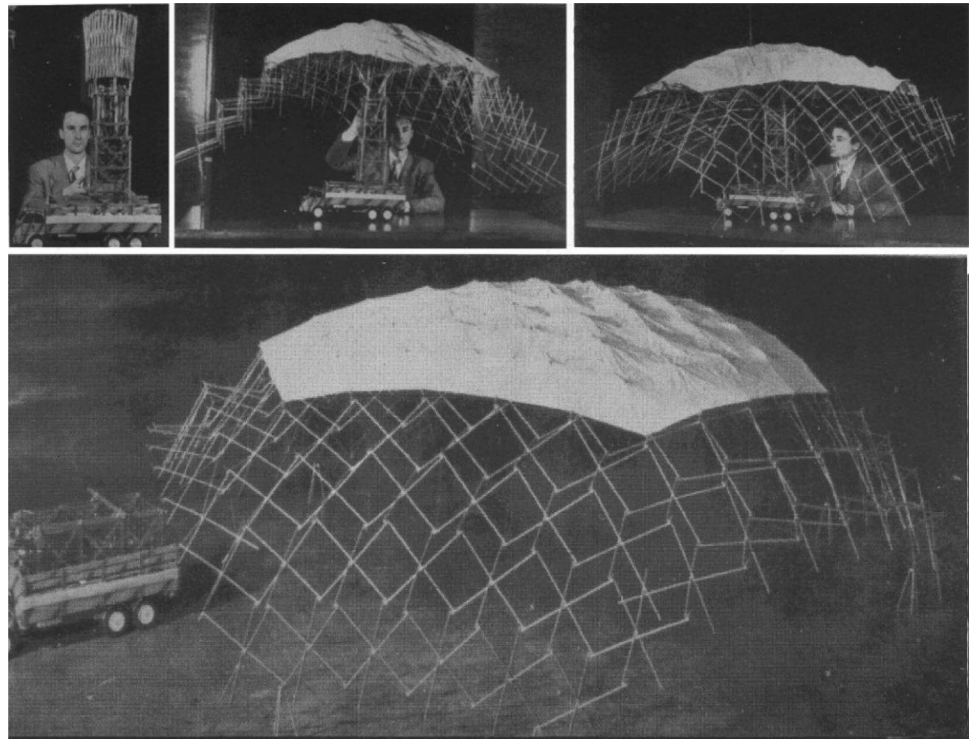
Deployable structures may change and assume different preset configurations in a predictable manner as they progress along pre-established paths in a controlled and secure manner. These features excellent material efficiency, modular design, ease of transportation and construction, and economical use of natural energy resources contribute to the building's overall sustainability [67]. There has always been a demand for compact, lightweight constructions that are simple to assemble and disassemble for personal use. Most of these lightweight structures were constructed on-site from simple linear sections wrapped in stiff fabric or panels. Modern deployable structures are built in a factory with their component parts integrated to meet predetermined geometric requirements [68]. There are applications of deploying techniques in sensitive structures such as large spatial structures which are needed for many current and future applications, satellites that are widely utilized in astronomy, space exploration, communication, and Earth monitoring, space shuttles and other launch vehicles which have finite size and probably always will [69]. The actuation system and the structural system are the two main parts of deployable structures. The actuation system can be accomplished by various technology ways or human contact, even though both components are necessary [70]. Over the past 10 years, the popularity of structures with movable parts has increased. Examples of these include bridges that open to allow ships to pass, revolving restaurants atop skyscrapers, sliding roofs in baseball and soccer dome stadiums, and artistic monuments. These constructions might be readily moved using hinges or rails [12, 71]. Morphing structures are shaped differently according to their purpose. It is heavily relied upon in engineering applications, particularly in flight, for system organization and control. Through morphing structures, engineers were able to enhance wing designs. Structures that change in shape are inspired by natural forms, like a bird's wing [72]. Spanish architect Emilio Pérez Piñero, the pioneer of scissor-like structures who focused on developing real structures, designed a deployable theatre using pantographic structures as shown in Fig. 4 [73]. Also, in Fig. 5, expansion of triangulated geodesic dome from angulated units is shown [73].

**Fig. 3** Example wall module for standard wooden-frame construction, where WF is width of frame beam, HF is height of frame beam, HP is thickness of plate, HT is thickness of wall [66]





**Fig. 4** Emilio Pérez Piñero and his design for a deployable theatre [73]



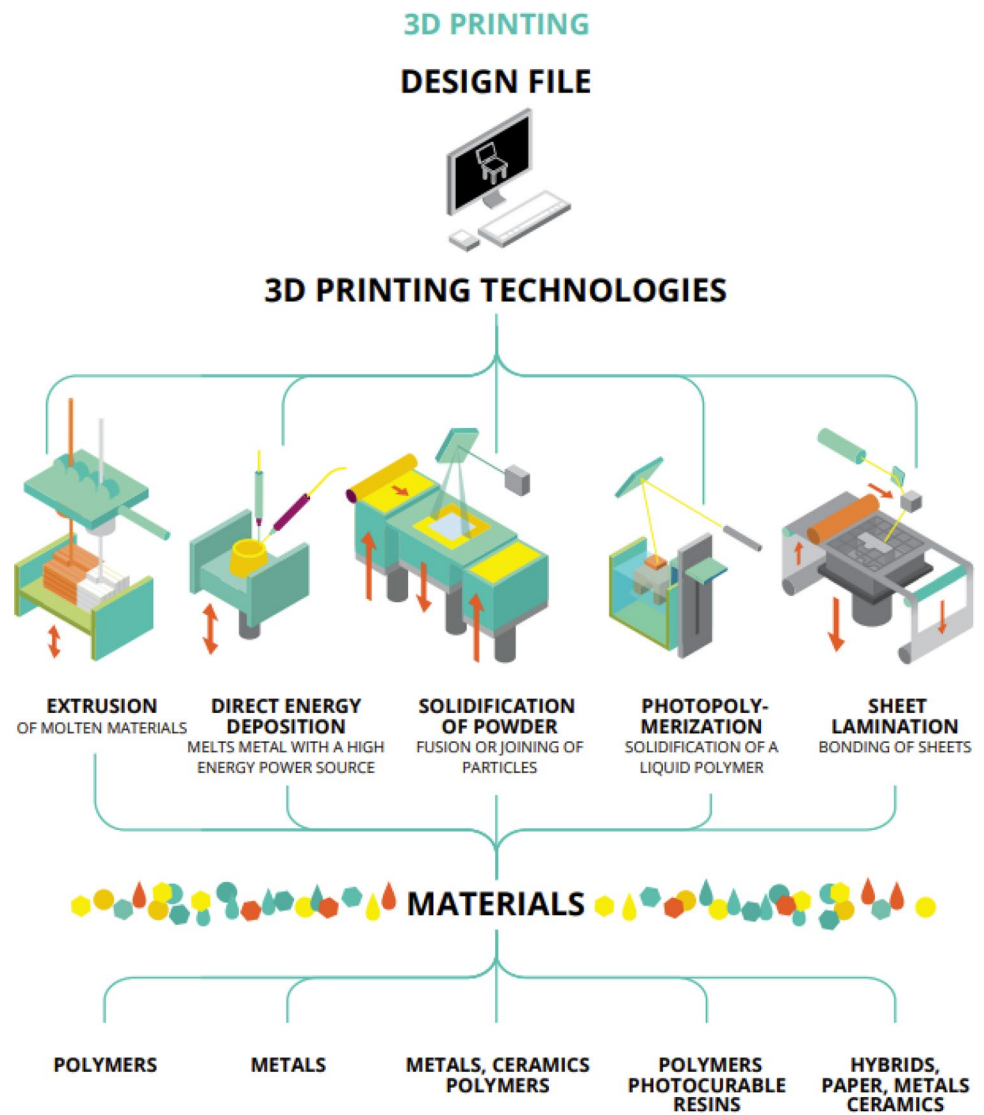
**Fig. 5** Expansion of triangulated geodesic dome from angulated units [73]



## 2.2 3D printing

3D printing (Fig. 6), also known as additive manufacturing (AM), rapid prototyping (RP), or solid-freeform (SFF), is the process of linking materials to make products from 3D model data, often layer by layer [74]. The aerospace and medicinal sectors have seen a rise in the usage of 3D printing, and the building industry is also considering this technology, with the construction of metallic structural elements and connecting nodes. Compared to conventional production methods, additive manufacturing (AM) offers a number of benefits, such as improved structural efficiency, geometric flexibility, customizability, and reduced resource consumption. Additionally, it permits prestressing, functionally graded materials, and other choices for strengthening and repairing [75]. Over the last 30 years, 3D printing has progressed beyond prototypes to being a viable manufacturing alternative for end-use items [76]. Arefin et al. [77] suggest that polymer 3D printing will become more widely used in industry. A range of materials, such as composite, metal, ceramic, and polymer, are used by various 3D printers. In 3D printing, polymers, and polymer-based composites are often utilized, especially in the production of fused filaments. includes a variety of fillers such as ceramic and metal nanoparticles. Except for directed-energy deposition, polymers are often employed in 3D printing. It is possible to modify polymers, such as thermoplastics and photopolymers, to fit certain printing applications and procedures [78].

**Fig. 6.** 3D Printing procedure with materials [79]



### 2.3 Advanced joining technologies

Creating effective and flexible structural connection processes is crucial for manufacturing, maintaining, and replacing components in a range of sectors at a reasonable cost. Industrial joining technique includes adhesive bonding, welding, and mechanical fastening [80] (Fig. 7). For modern composite structural elements, bolted or hybrid bolted/bonded connections continue to be the most popular fastening mechanism. Mechanical fasteners are insensitive to surface preparation, service temperature, and humidity conditions, and may be removed without resulting in structural damage. Experimental data and empirical models are the main tools used in the design of mechanically linked joints in composite materials [81]. Kumar Rajak et al. [82] explained the properties of welding and stated that, because friction-based welding uses less energy and produces a stronger welded connection, it is a very effective and eco-friendly method of joining solid-state metals. In order to fuse materials together, these technologies rely on high temperatures produced by friction. In the other hand, Marković et al. [83] investigated adhesive connections and compared it with mechanical and welding technologies and stated that, since adhesive connections are thin and have a low specific weight, they have benefits over welded and mechanical connects. Adhesion-related joining needs to be strong enough to bear heavy loads, evenly distribute force, light enough to save weight, improve component stiffness and longevity, and crash test positive. These adhesives include benefits in reduced heat impact, reduced vibration, and enhanced sealing.

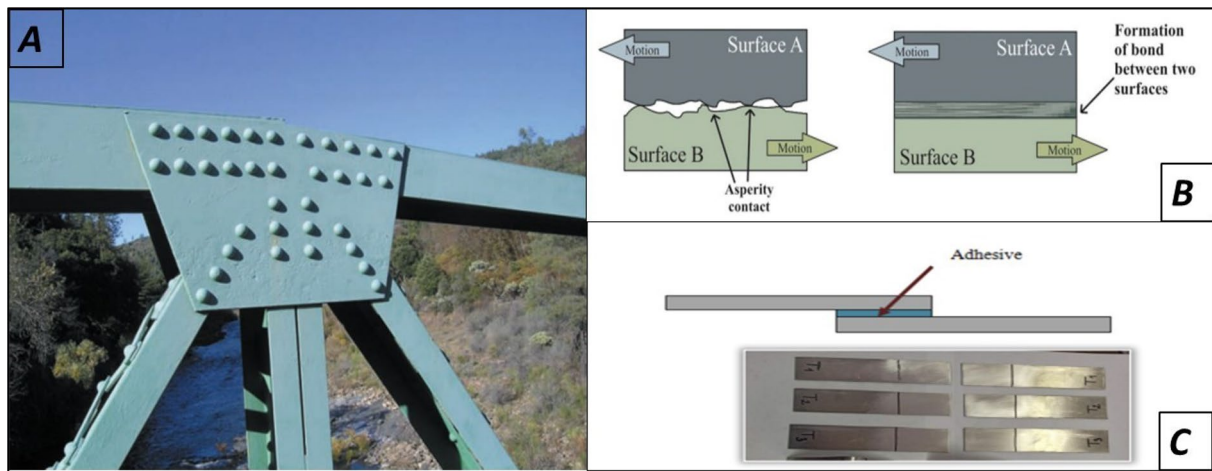


Fig. 7 **A** Bolt connection [84], **B** friction based welding [82], **C** adhesive connections [83]

## 2.4 Embedded sensors and actuators

To carry out specific duties, smart structures integrate structures, sensing, actuation, control, and signal processing components. Due to their application in fields including aerospace, civil engineering, maritime applications, automobiles, precision instruments, and machinery, they are growing swiftly [85]. Developing embedded sensors (ESs), smart materials, and smart structures presents considerable problems in engineering research. Innovation in sensors and sensor systems is critical to the growth of smart structure technologies [86, 87]. Saeed [12] outlined the many actuator types that may be utilized in smart structures shape control, such as piezoelectric actuator, shape memory alloy, lead screw, and thermal effect, and said that actuator location is crucial for the optimal control of a structure. Actively controlled smart electro-magnetic materials open up new opportunities for mechatronic systems, structural systems, gadgets, and structures that are accurate and high performing. Fully integrated smart structures and structural systems are made possible by the enhancement of conventional mechatronic devices through the integration of smart materials, sensors/actuators, control electronics, computers, and artificial intelligence [88]. Different types of actuators and their properties are shown in Table 2 and Fig. 8.

**Table 2** Different types of actuators and their properties

Type of actuator	Properties
Mechanical actuator (turnbuckle)	<ul style="list-style-type: none"> <li>The turnbuckle is made up of two threaded eye bolts inserted into a tiny metal frame, one with a left-hand thread and the other with a right-hand thread [89]</li> <li>It adjusts the length and force of tension wires or rods [90]</li> <li>The typical turnbuckle cannot measure tensile tension but may be modified by rotating its body [90]</li> <li>The conventional turnbuckle may be used without modification, even if the tensile tension has shifted over time [91]</li> </ul>
Thermal effect	<ul style="list-style-type: none"> <li>Heating effects can be employed to regulate a large-area system, effectively reducing static distortion induced by distorted geometry [89]</li> <li>Active members need a high coefficient of thermal expansion [12]</li> </ul>
Piezoelectric	<ul style="list-style-type: none"> <li>These are the most popular intelligent materials for shaping systems [89]</li> <li>It is possible to manufacture distributed piezoelectric control systems that are very precise, efficient, and lightweight [92]</li> <li>Piezoelectric sensors can detect movement, velocity/acceleration, slope, and slope rate [92]</li> </ul>
Shape memory alloy	<ul style="list-style-type: none"> <li>This product stands out for its exceptional qualities, which include great strength, a large range of motion, a small size, and a lightweight construction [89]</li> <li>These components can be passive, semi-active, or active, minimizing damage from environmental factors or earthquakes [93]</li> <li>Mostly used in laboratories, few have been tried out in the field and proven successful [93]</li> </ul>

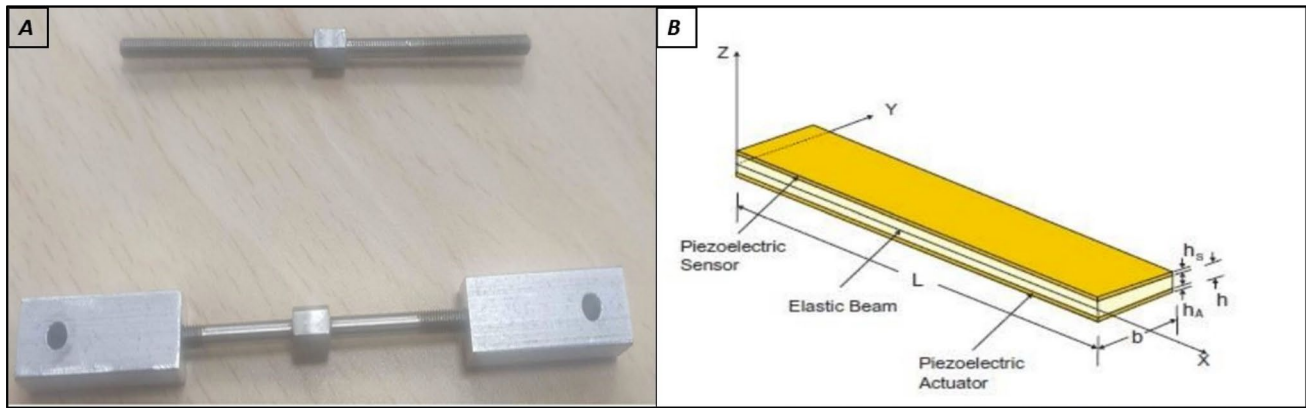


Fig. 8 **A** A mechanical actuator (turnbuckle) [89], **B** a laminated beam with piezoelectric sensor/actuator [94]

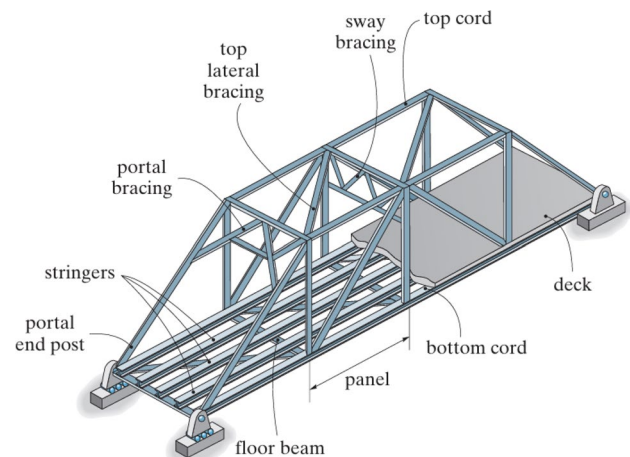
### 3 Types of lightweight structures

There are several kinds of lightweight structures within the field of structural engineering, and they may be categorized according to the material type, shape, and forces produced by their members. Several of these kinds of structures are mentioned in this study.

A truss is a type of structural element made up of thin sections that are connected at both ends. Channels, angles, metal bars, and timber struts are often utilized parts in buildings. The ends of the members are often bolted or welded to a common plate known as a gusset plate to provide the joint connections [95]. Figure 9 illustrates the basic structural components of a typical bridge truss. The floor beams, side trusses that support the deck, and stringers share the weight of the structure. To bear the strains of wind and vehicles, the top and bottom cords of the side trusses are braced laterally [95]. The produced stress in truss members is always compression or tension.

Pantographs are sometimes known as scissor-like components that can be used in different applications for morphing and deployable structures [12]. Glisic et al. [96] described pantographs as movable structures that have the ability to expand from a compact, tiny state while supporting weights. The pantograph components consist of two straight bars with their ends left free and connected by an "intermediate hinge" around the middle of the bars. Pantographic structures may be constructed using a variety of fundamental unit kinds, such as translational (Fig. 10), polar (Fig. 11), and angulated units (Fig. 12), by adjusting the placement of the intermediate hinge and bar form [12, 97]. For example, as shown in (Fig. 4), symmetrical plane when the intermediate hinge is in the middle of both bars, symmetrical curved when the intermediate hinge is in the middle of only one bar, and non-symmetrical curved when the intermediate hinge is not in the middle of any of two bars. Pantographs are considered complex element structures since two macro components are connected by a shear connection and their two ends are connected by pins. The fact that only pin joints are susceptible to external forces must be emphasized [98].

Fig. 9 Fundamental structural elements of a standard bridge truss [95]



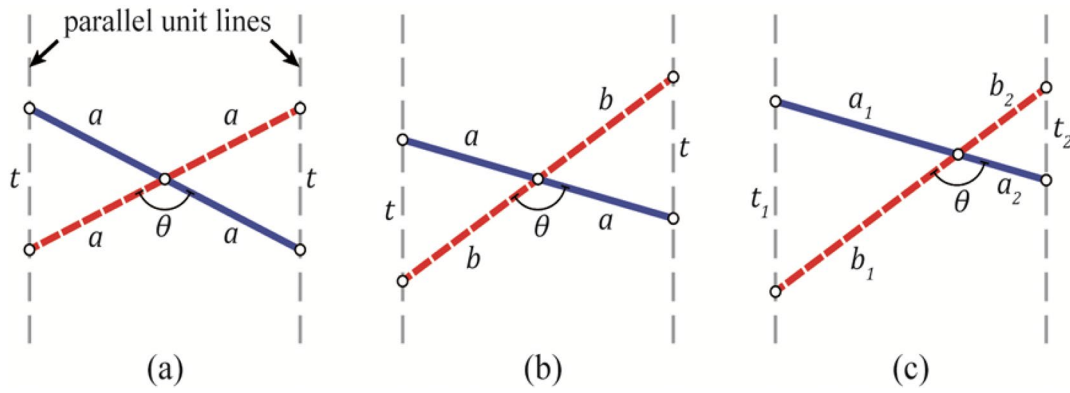


Fig. 10 There are three types of translation units: **a** symmetrical plane, **b** symmetrical curved, and **c** non-symmetrical curved [97]

Fig. 11 Polar unit [12]

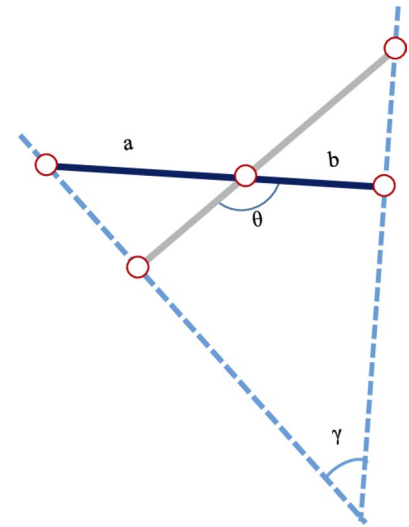
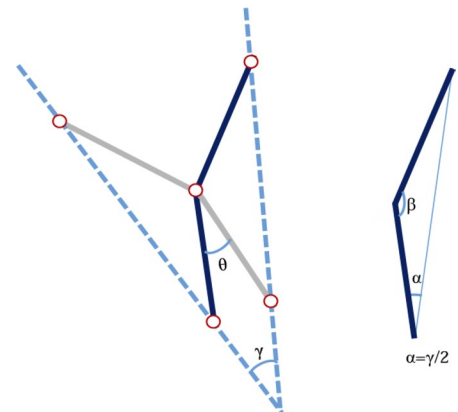
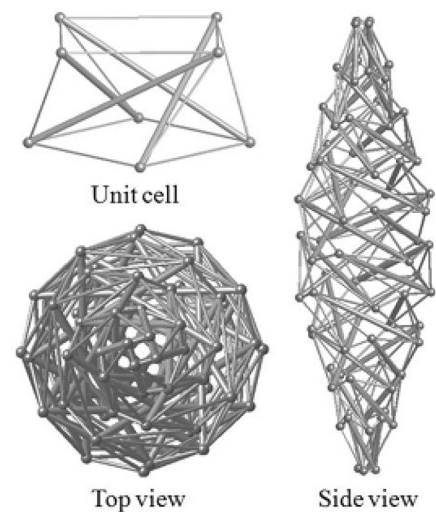


Fig. 12 Angulated unit [12]



One of the most complex lightweight structures is tensegrity structures as shown in Fig. 13. Richard Buckminster Fuller coined the term tensegrity as a contraction of ‘tensional’ and ‘integrity’ [99]. Continuous tension members, like cables, and discontinuous compression elements, like struts, balance a structure’s stability. Whereas the struts are stiff local components, the cables are flexible global components [100]. Low load responsiveness and intricate precision fabrication are the main problems and disadvantages of actually using tensegrity technology [101]. Prestressed pin-jointed tensile structures, or tensegrity structures, are free-standing and have both compressive and tensile components. These characteristics set them apart from traditional pin-jointed structures [100]. Structures known as tensegrities are flexible

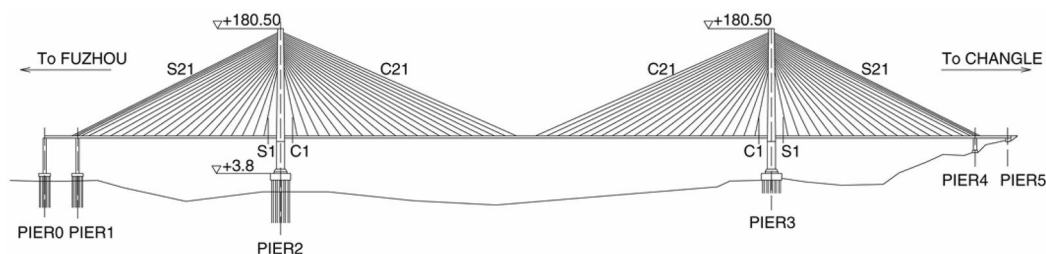
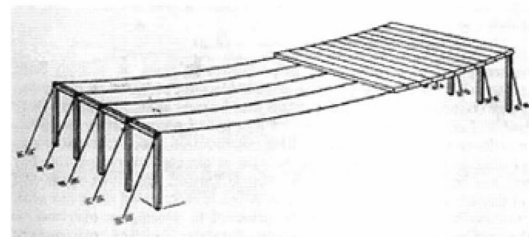
**Fig. 13** Self-equilibrium arrangement of the ten-layer tensegrity tower using the force density approach [103]



enough to react to varying forces and minute alterations in their surroundings. Consequently, their decisions are typically based on serviceability standards. By modifying their personal stress levels, individuals can fulfill these demands. Active tensegrities can change form in response to changing activities and conditions since they are equipped with sensors and actuators [102].

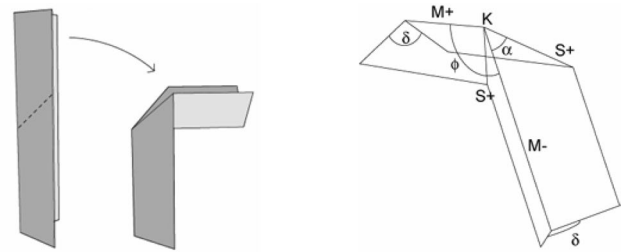
Scholars have been interested in studying cable-based constructions for a while now. The interplay between stress and strain makes the situation complicated. Due to their extreme nonlinearity, cables exhibit geometric nonlinearities at large displacements. Cable constructions exhibit a range of actions [104]. Cable structures, such as main cables for suspension bridges, stayed cables for cable-stayed bridges, and arch bridge hangers, are widely used in bridge engineering. Cost-effective and aesthetically pleasing, cable bridges are a great choice. Over the past 20 years, there have been considerable developments in both the design and construction of long-span bridges, making them the preferred solution globally [105]. Beam column systems and simply hanging cable constructions are similar in that the “beam” supports loads through tension rather than bending. The resultant architectural forms have a roof that is overly deflected but otherwise resembles regular structures. Vertical wires can be arranged parallel to one another on rooftops that are trapezoidal or rectangular in shape as shown in Fig. 14 [106]. Cable-stayed bridges as shown in Fig. 15, were built beside suspension bridges, but when the Tweed and Saale River bridges fell at the beginning of the nineteenth century, they were abandoned. Roebbling and others employed cable-stays to prevent suspension bridges, such as the Brooklyn Bridge, from buckling [107].

**Fig. 14** Simply hanging cable roof with a rectangle design [106]

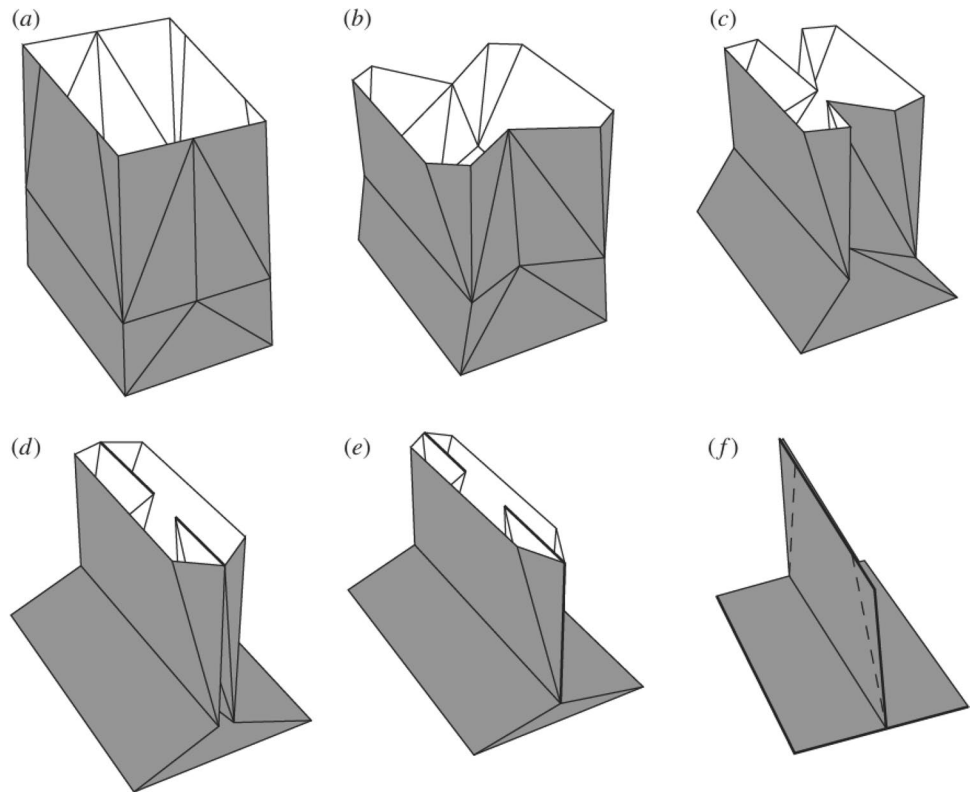


**Fig. 15** Schematic illustration of the Qingzhou cable-stayed bridge [108]

**Fig. 16** Reverse fold of origami [110, 111]



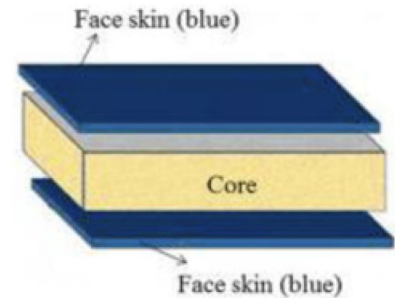
**Fig. 17** Animation showing the folding process of a bag from (a) to (f) along this specific path [113]



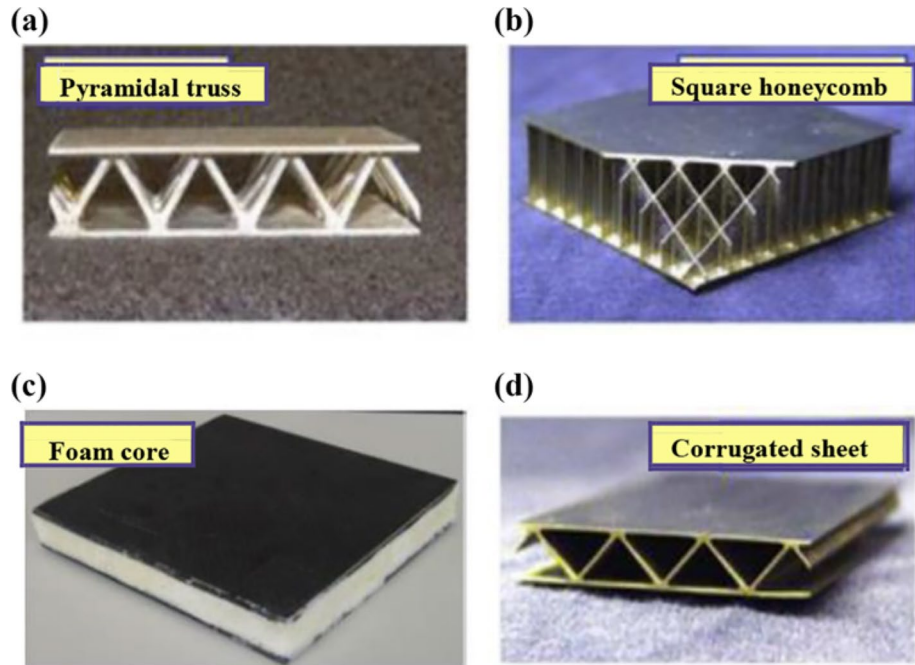
Originating from the Japanese terms *oru* (to fold) and *kami* (paper), origami is the age-old craft of folding paper. No tearing, cutting, or gluing is permitted while folding traditional origami; only straight folds on a square sheet of paper are required. Origami may be folded to form a flat plane that can be unfurled to create a developable surface [109]. The reverse fold is one of the fundamental skills of origami [3]: a diagonal crease can bend one parallel fold. A straight parallel fold bends and reverses from mountain to valley [110, 111] as shown in Fig. 16. A multitude of three-dimensional structures, including thin-walled tubes and arcs, may be constructed with different sheet materials thanks to the profusion of crease patterns. Sandwich plates, arcs, and core structures can all be made out of origami. Metamaterials, or materials having special qualities not present in nature, may also be made by layering them. The mechanical performance of these structures can be enhanced by optimizing their geometric characteristics [112]. Wu and You [113] applied origami principles as a solution to folding rigid tall shopping bags as shown in Fig. 17.

Sandwich structures are multilayered composite constructions that are intended to resist predicted lifetime loads. A sandwich structure consists of outer facings with a core placed between them [114] as shown in Fig. 18. Sandwich structures are being used more and more in a wide range of applications, including wind energy systems, bridge building, vehicles, trains, airplanes, and satellites. Due to its many benefits, the development of new materials, and the need for high-performance, lightweight constructions, sandwich construction will remain popular [115]. Popular core definitions include truss, foam, corrugated, and honeycomb cores (Fig. 19). Sandwich constructions are finding increasing usage in a variety of fields, including wind energy systems, bridge construction, automobiles, trains, aircraft, and satellites. Sandwich construction will continue to be popular because of its many advantages, the creation of new materials, and the demand for high-performance, lightweight structures. Corrugated cores, as seen in Fig. 19d, usually contain open

**Fig. 18** Sandwich structure  
[116]



**Fig. 19** Typical sandwich structures include pyramidal trusses, square honeycombs, foam cores, and triangular corrugated sheets, the three types of inner structures that are repeatedly repeated are honeycomb, corrugated, and truss. When compared to foam, the core region's repeatedly repeated inner structures produce more empty volume [116]



channels in just one direction. Unlike corrugated cores, honeycomb cores often feature closed-cell forms such as hexagonal, square, and square honeycombs.

## 4 Applications of lightweight structures

### 4.1 Aerospace and robotics

In various industries, particularly in aerospace applications, the notion of light weighting design has been thoroughly investigated and applied [39]. Many of the activities being explored by the earth science and space scientific communities need large space systems, i.e., those with apertures greater than 15 m or diameters more than 20 m [117]. To achieve lightweight design for aeronautical components and systems, advanced lightweight materials are typically employed to numerically optimize designs that may be fabricated using appropriate processes. Therefore, by adopting cutting-edge lightweight materials, it is feasible to efficiently reduce weight and boost performance [39]. In recent decades, pressure has been applied by numerous groups to improve safety and lessen the negative environmental effects of aeronautical structures in order to transport people and goods more affordably and competitively [118]. The first industries to encounter problems with light weighing were aerospace and aircraft manufacturing. Gaining extensive design experience is equally as crucial as becoming an expert in theory. To address the challenges they face with lightweight systems, lightweight engineers are facing more demands to expand their knowledge and use their experience in new ways [2]. The aerospace industry prioritizes lightweight construction to decrease fuel consumption and carbon emissions [119].



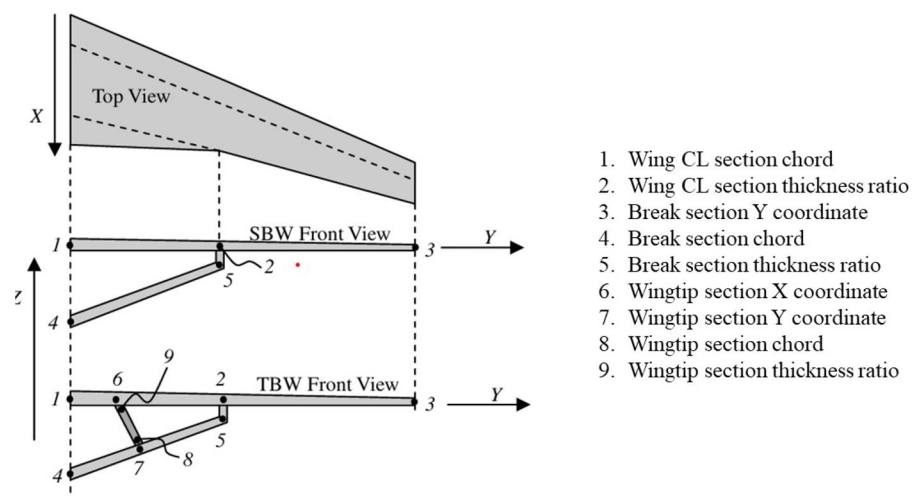
There were several notable projects in robotic building investigating alternative fastening techniques for structural components [117]. We go over a few examples of flexible lightweight structures in robotics and aerospace engineering below since these assemblies have several uses in the robotics sector because of their active functioning and flexibility.

The advantages of a truss-braced transonic transport aircraft configuration over cantilever-wing and strut-braced wing configurations are established in [120]. Three types of aircraft wings, the cantilever, the strut-braced wing (SBW), and the three-member truss-braced wing (TBW) with increasing topological complexity are produced through multidisciplinary design optimization. Their design methodology employs a multidisciplinary design optimization (MDO) architecture that has modules for weight estimations, aerodynamic analysis and design, and structural design in addition to other elements such as an optimizer and propulsion module. Three distinct target functions [lowest takeoff gross weight (TOGW), lowest fuel/emissions, and maximum lift-to-drag ratio] were used in the MDO results, along with two aerodynamic models (aggressive technology and current technology) and three fundamental configurations (cantilever, SBW, and Jury-TBW). Figure 20 shows the operational and geometric design variables that exist in the cur TBW installation. For the aggressive-technology instance, nine of these concepts are shown in Fig. 21. The findings show that wingspan may be increased, and generated drag can be decreased by using truss members. Together with the elements of wave drag and friction, the wing chord and thickness also decrease. These patterns come from better structural behavior. Therefore, smaller sections and greater aspect ratios are achievable for the same weight. The primary advantage of including a supporting truss in a wing construction is decreased spanwise bending moments for a given load. As a result, the wing construction becomes lighter and allows for a decrease in section thickness, an increase in span, and a drop in chord.

A further consequence of the wider wingspan is the longer and thinner truss members, whose buckling-load capability is often inversely correlated with the square of the member length. This has greater significance for the SBW design than for the TBW since the support members of the TBW are often shorter. A fuselage fuel tank is needed since the small, thin wing cannot contain as much fuel. When the target function is minimum-TOGW, the SBW and TBW layouts exhibit reduced wing weight for the same span and wing aspect ratio (AR). The wing skin thickness map shows this as well in Fig. 22. It is clear that a truss greatly lowers the skin thickness in the wing's inboard section, which lowers the weight of the wing. The greater span and AR of the SBW and TBW designs enhance the lift-to-drag ratio  $L/D$  for the instances of the minimum fuel/emissions target function by lowering the generated drag. Furthermore, the zero-lift drag coefficient is lowered by the higher cruising altitude and wing area. As a result, both fuel weight and TOGW decrease as shown in Fig. 23.  $L/D$  values of the highest  $L/D$  and optimal minimum-fuel designs are more than twice as high as those of the current generation of commercial aircraft. These high  $L/D$  ratios are indicated by high spans and ARs as shown in Fig. 24 [120].

As an alternative to the conventional aerofoil Fig. 25, Saeed and Kwan [72] discovered suitable morphing aerofoil structures employing pantographic structures that result in the higher lift ( $CL$ ) and reduced drag ( $CD$ ) coefficients. The basic aerofoil NACA2415 serves as the foundation for the comparative study, and a series of connected, curved, single-actuator pantographs is employed to create the intricate morphing aerofoil structures. Two setups have been looked at in detail. While the first lacks many large pantographic parts, the second has a lot of minor pantograph bits. The first structure has fewer large pantographic units than the second, which has more little ones. Aerofoil structures use varying camber, leading, and trailing edge designs to manage attitude and adapt to changing air conditions. Fundamentally, both

**Fig. 20** Geometric design variables [120]



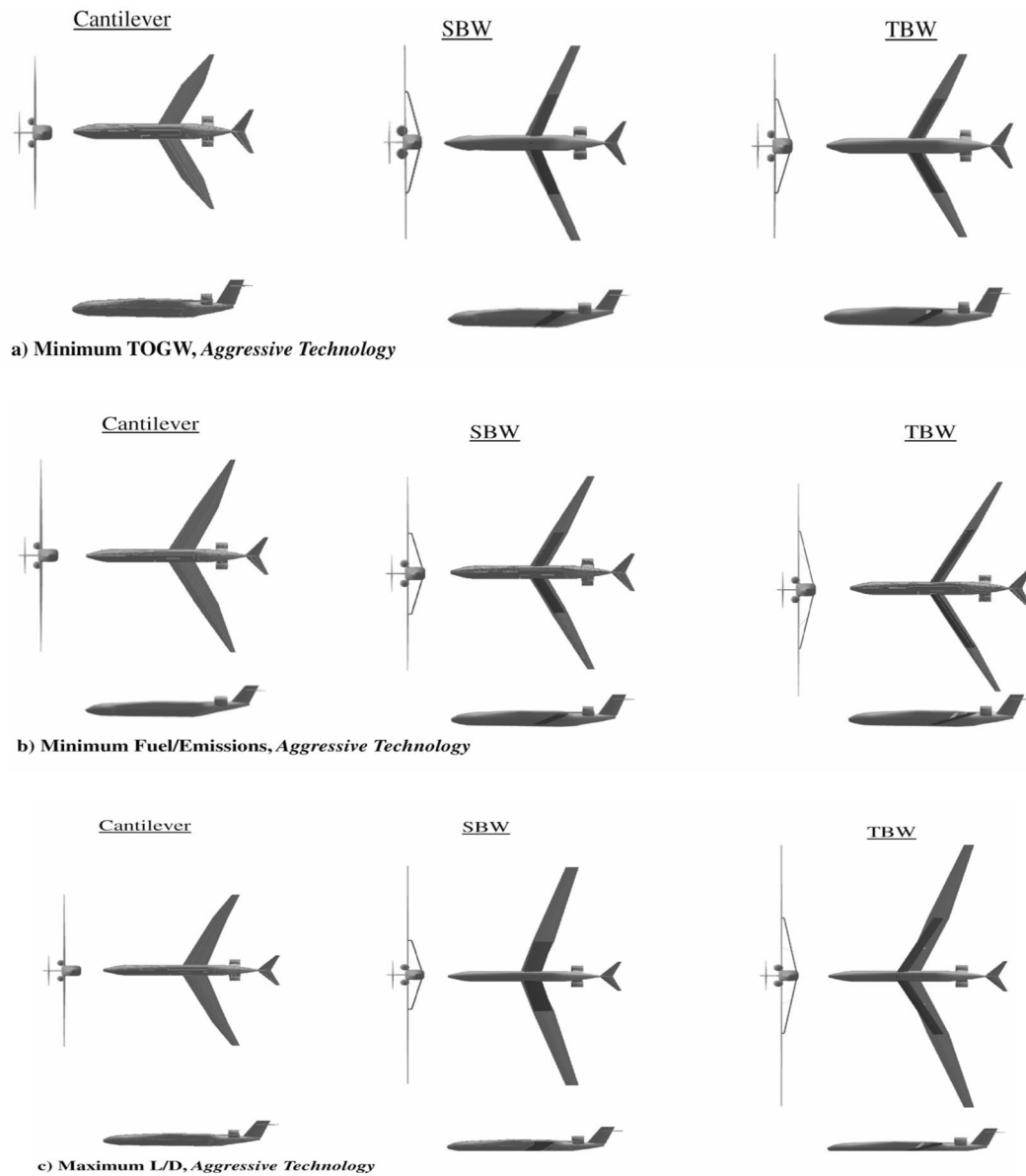
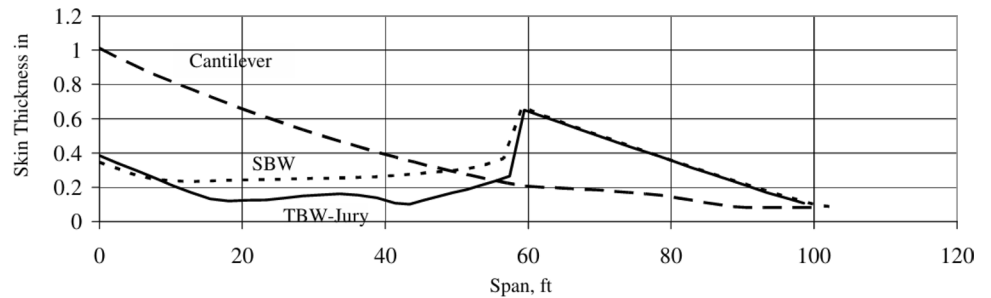


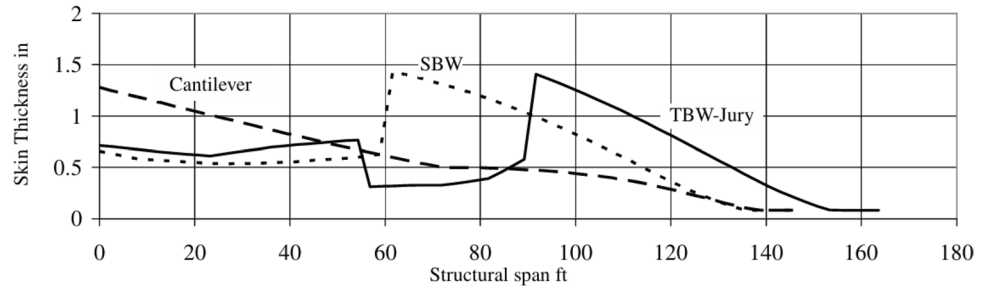
Fig. 21 Optimal design configurations for aggressive-technology cases [120]

Fig. 22 Optimal design configurations for aggressive-technology cases [120]

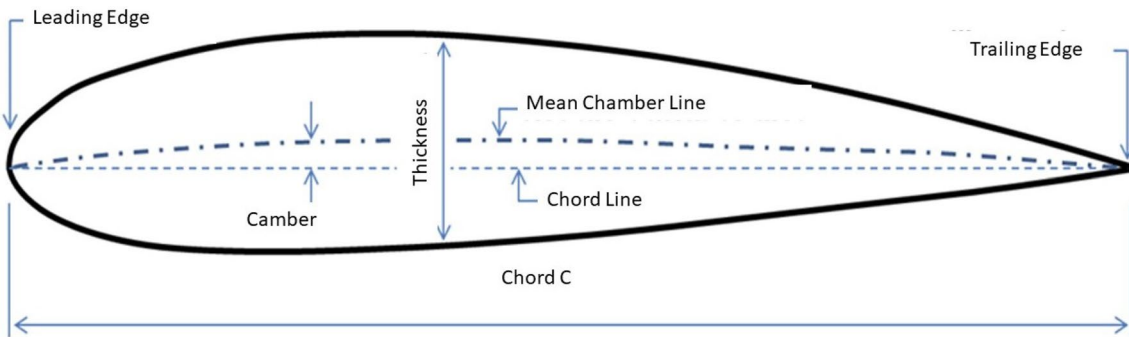
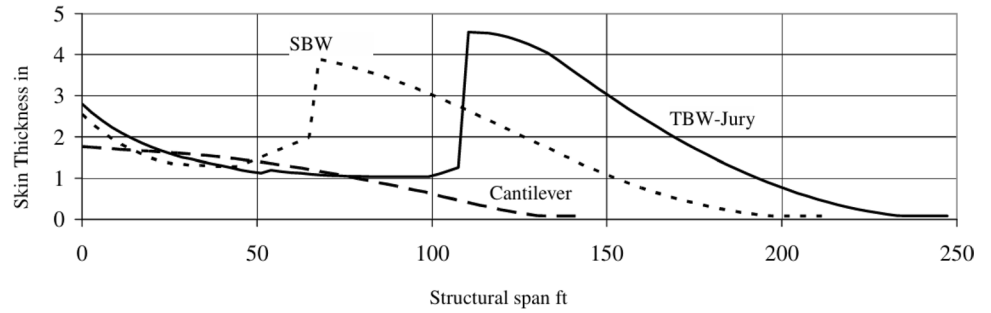


aerofoils are made up of interconnected, curved pantographs that are managed by a single control. Every pantographic unit is made up of two beams joined by a shear connection. Figures 26 and 27 show the nine morphing phases of the configurations of morphing structures one (MAS1) and two (MAS2) in order to illustrate the cross-sectional variation that morphing produces. These two designs for morphing aerofoils may not be suitable owing to the lower cross-sectional

**Fig. 23** Optimal design configurations for aggressive-technology cases [120]

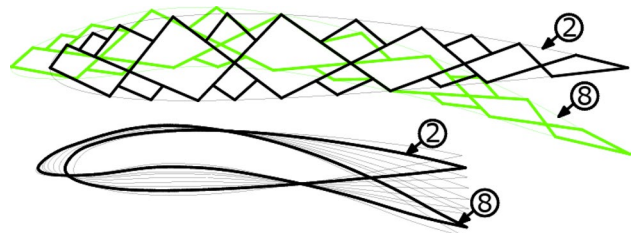


**Fig. 24** Optimal design configurations for aggressive-technology cases [120]

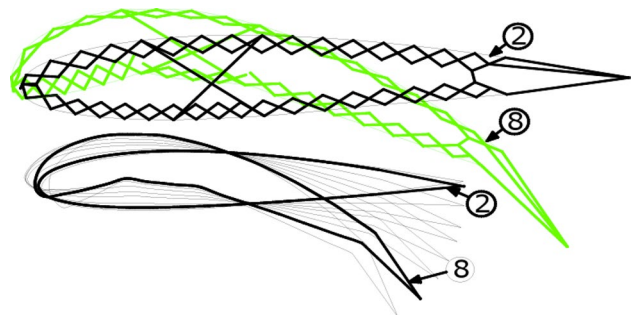


**Fig. 25** Aerofoil terminology [72]

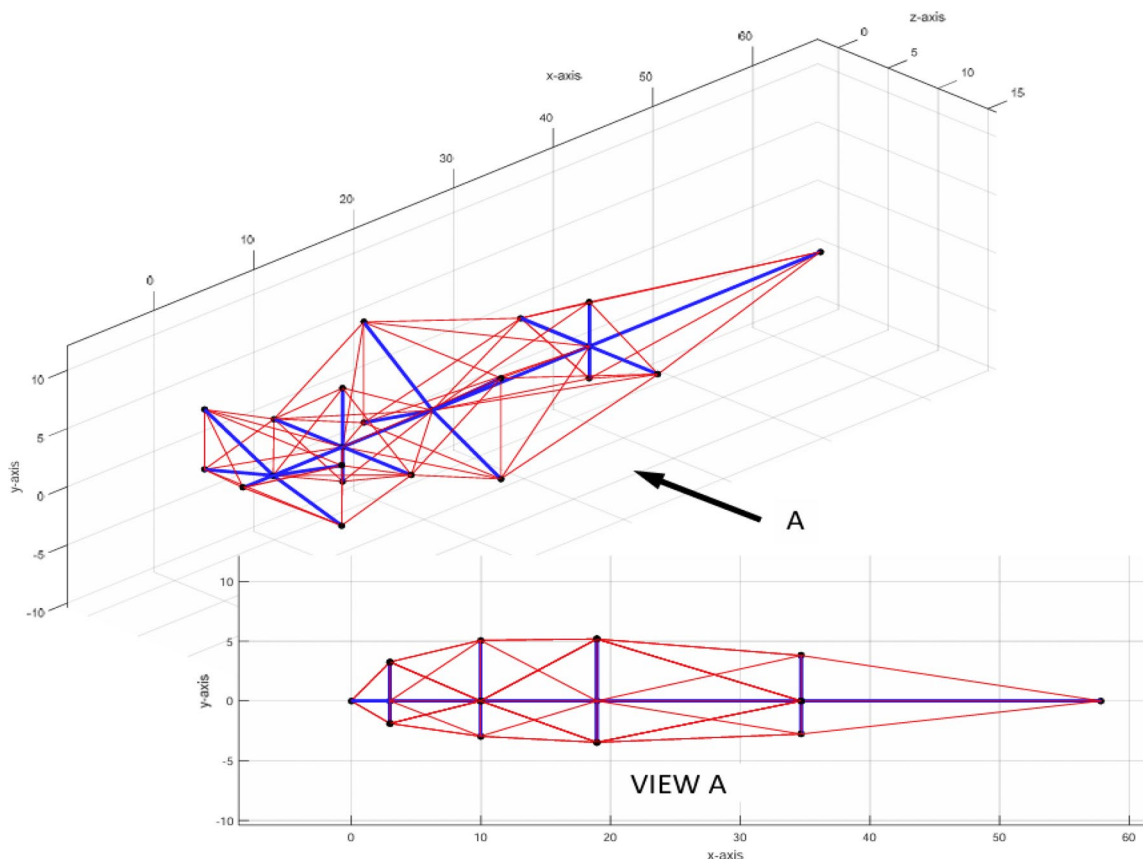
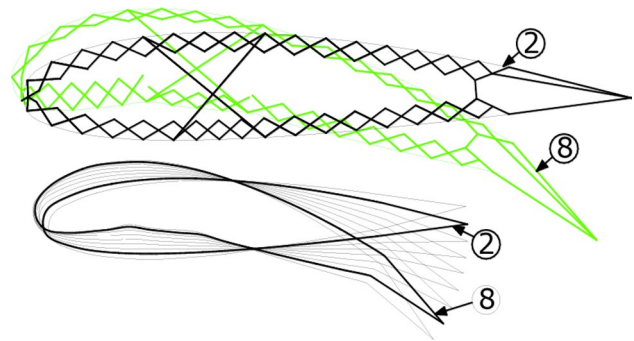
**Fig. 26** Nine morphing stages of proposed MAS1 [72]



**Fig. 27** Nine morphing stages of proposed MAS2 [72]



**Fig. 28** Nine morphing stages of MAS3 [12]



**Fig. 29** Four R-cross unit cells are combined to produce a tensegrity, rib-like structure. Cables are represented in red, while struts are displayed in blue [121]

area compared to NACA2415, which is commonly utilized for fuel storage on aircraft wings. As a result, an additional morphing aerofoil (MAS3) is proposed in Fig. 28 [12].

The simulated structural performance of conventional wings and tensegrity aircraft wing concepts are compared. Systems are known as tensegrity by Mills et al. [121], which consist of cables and struts, provide lightweight structures with tension or compression loads while maintaining structural efficiency. Using engineering design principles, the rib-like structure seen in Fig. 29 was assembled from four rectangular-cross unit cells. It is important to observe that the four R-cross cells are spaced 45° apart. The struts' length is chosen to place nodes in the best locations that roughly correspond to the NACA 23015 airfoil. As seen in Fig. 30, eight rib-like segments are connected spanwise to produce a stable, complete wing tensegrity structure. Using the topology optimization formulation and the ground structure approach, a second tension-based wing design was produced for the comparison in the same study as shown in Fig. 31, This displays the positions of the ground structure's nodes as well. The three offset layers represent the root of the wing. Every layer that fits inside the NACA23015 airfoil has 14 possible nodes in a grid. When compared to the underlying structure (without

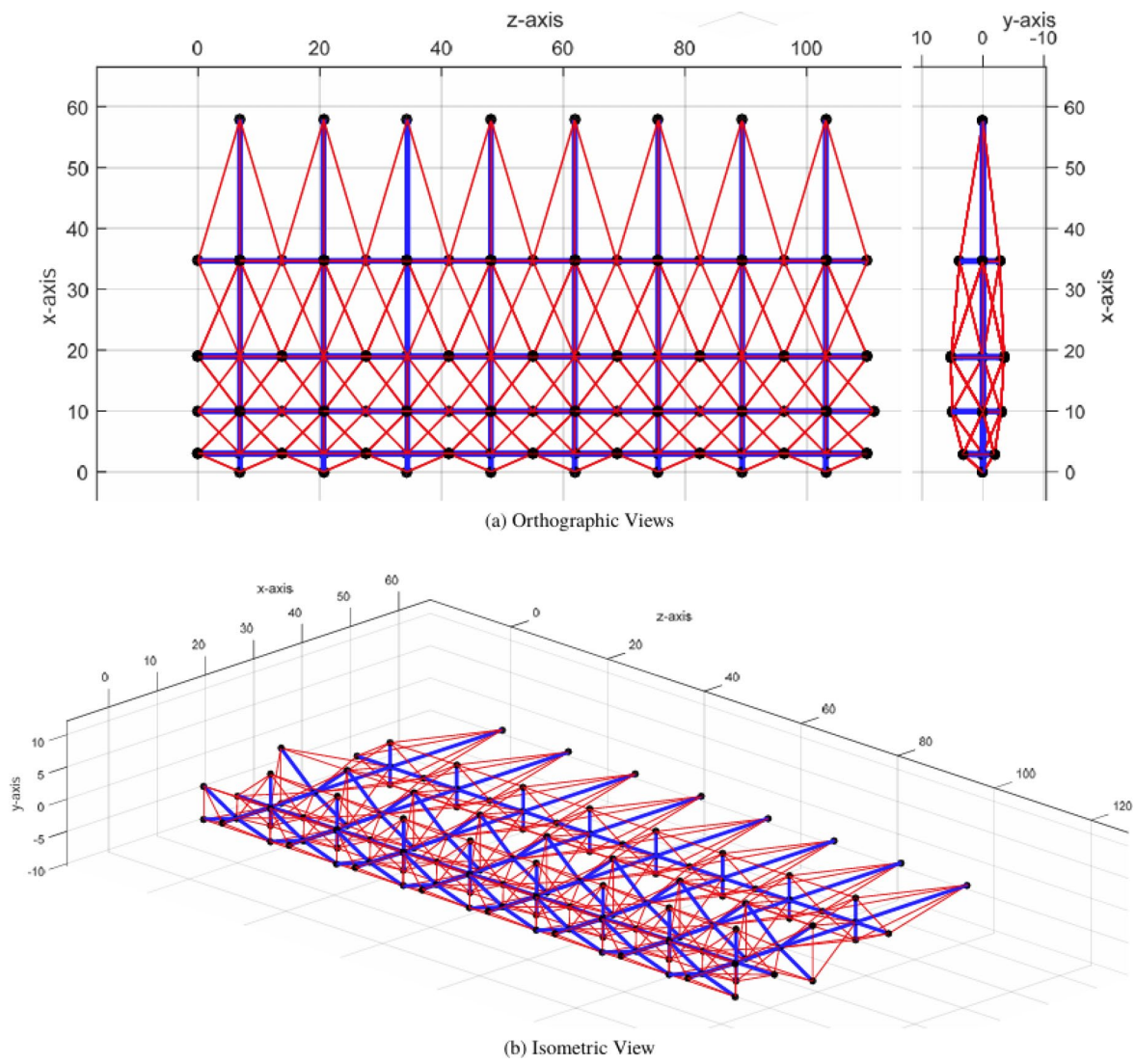


Fig. 30 Eight of the rib-like segments shown in Fig. 29 are combined to form the tensegrity wing concept [121]

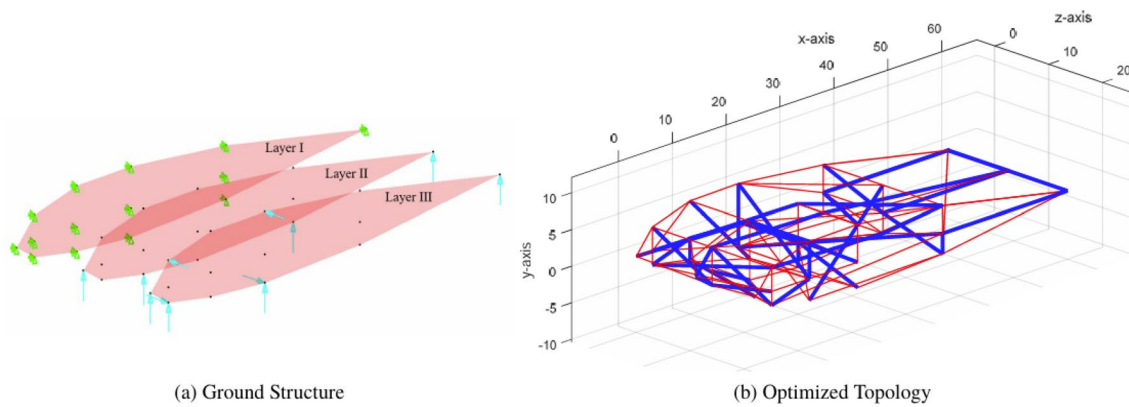


Fig. 31 The ground structure mesh utilized for the tensegrity topology optimization and appropriate optimization result [121]

skin), the topology-optimized wing weighed 49% of the baseline, while the resulting designer-developed tensegrity wing weighed 59% of the baseline. With less mass needed, tensegrity wings which are optimized for the topology may almost equal the maximum deflection of a conventional wing for any load situation, with or without skin. The weights of the conventional wings are 10.8 kg, while the masses of the tensegrity wings, omitting the skin, are 5.4 kg and 6.4 kg, respectively. The traditional wing weighs 25.7 kg, but the weights of the designer-developed and topology-optimized tensegrity wings Fig. 32, including the skin, are 20.1 kg and 21.3 kg, respectively.

Solar panels are one of the major deployable components of satellites as shown in Fig. 33. A high-performance deployable solar array system that can meet or exceed cutting-edge packaging efficiencies while delivering high power output is provided by the Structural Origami ARray (SOAR), in response to the growing need for increased power generation on small satellites for advanced electric propulsion or remote sensing instrumentation. A scalable, user-friendly modular origami folding approach with nearly perfect packing efficiency achieves these performance goals. Using thick cover glass and high-efficiency solar cells can prolong the array's operating life since it is not susceptible to array thickness [122]. The integrated lattice support structure with multi-axis compliant hinges that are placed at the panel intersection places make up the design. This concept preserves the folded array's packing efficiency by having the entire lattice structure stow approximately around the folding pattern's edge, making use of the unique folding kinematics of SOAR. Moreover, this structure may be freely deployed by using the strain energy stored in the distributed compliance mechanisms. Effective testing has demonstrated that the SOAR architecture operates as planned. Recurring deployment tests

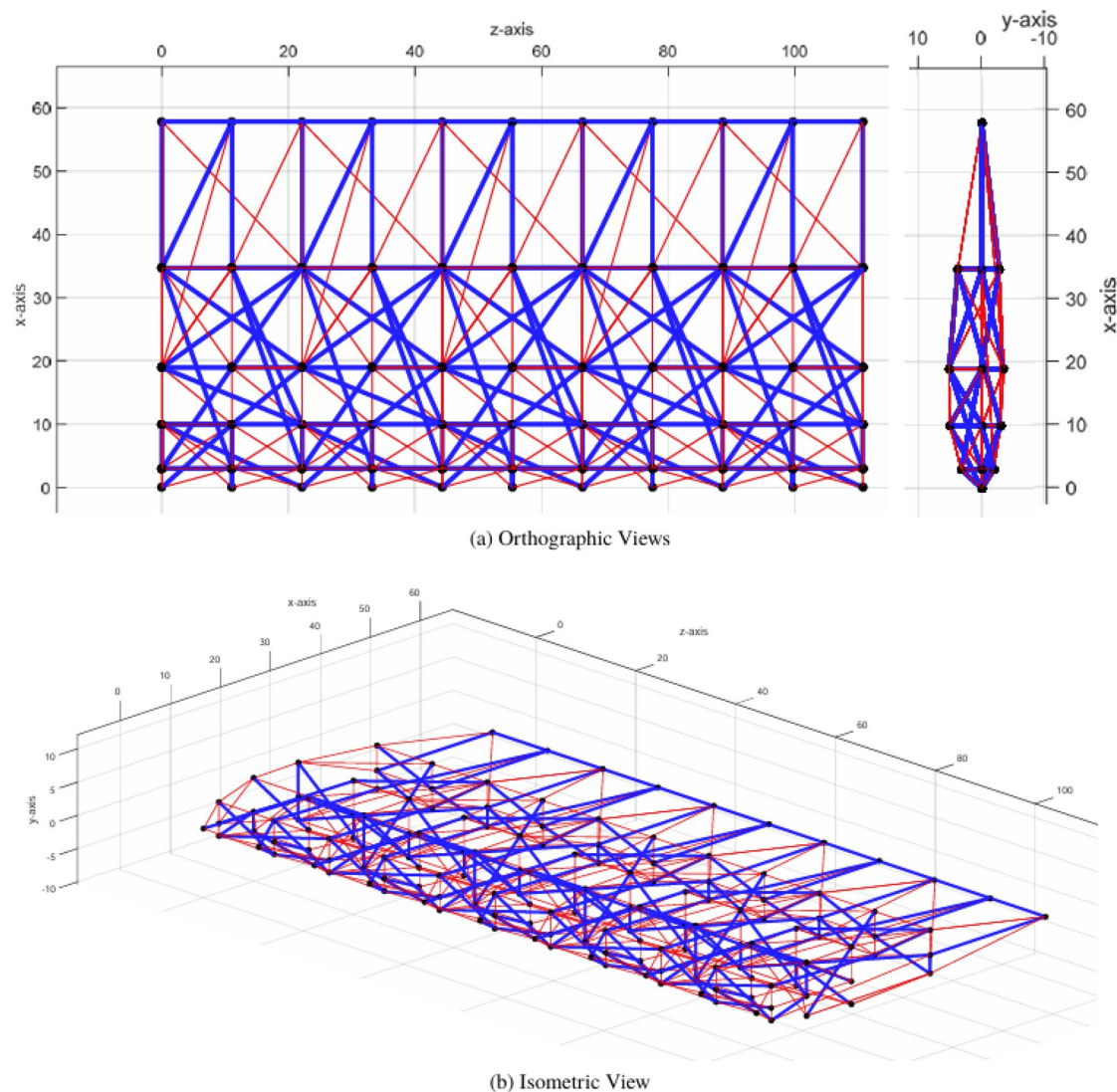
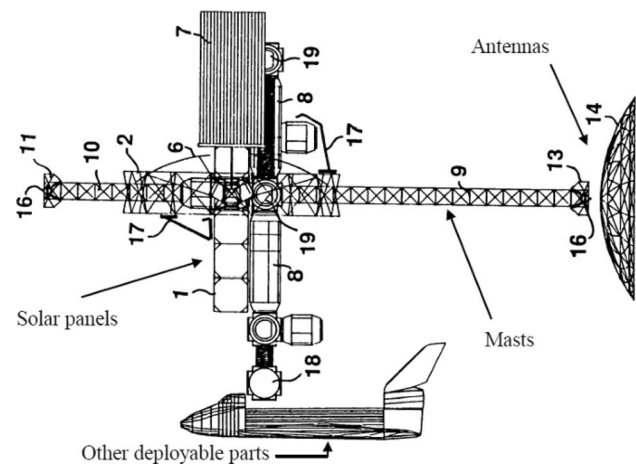
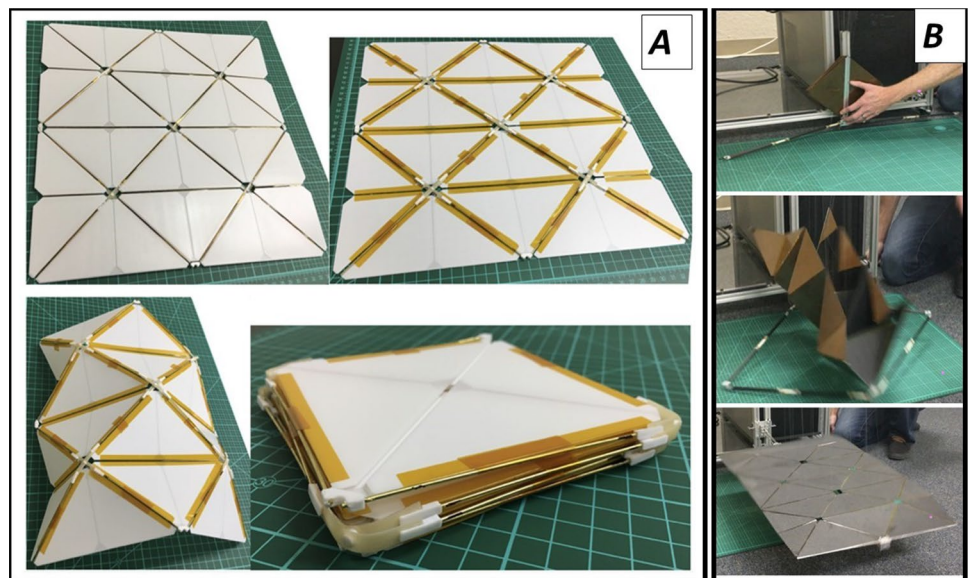


Fig. 32 The tensegrity wing concept was created by merging five topology-optimized rib-like segments shown in Fig. 31 [121]

**Fig. 33** An illustration showing the satellite's deployable parts [123]



**Fig. 34 A** The idea of a lattice support framework folds mounts in several places [122], **B** the shift from the thin, square stack in the stowed state to the final planar configuration is seen in the array deployment sequence from a free-deployment test [122]

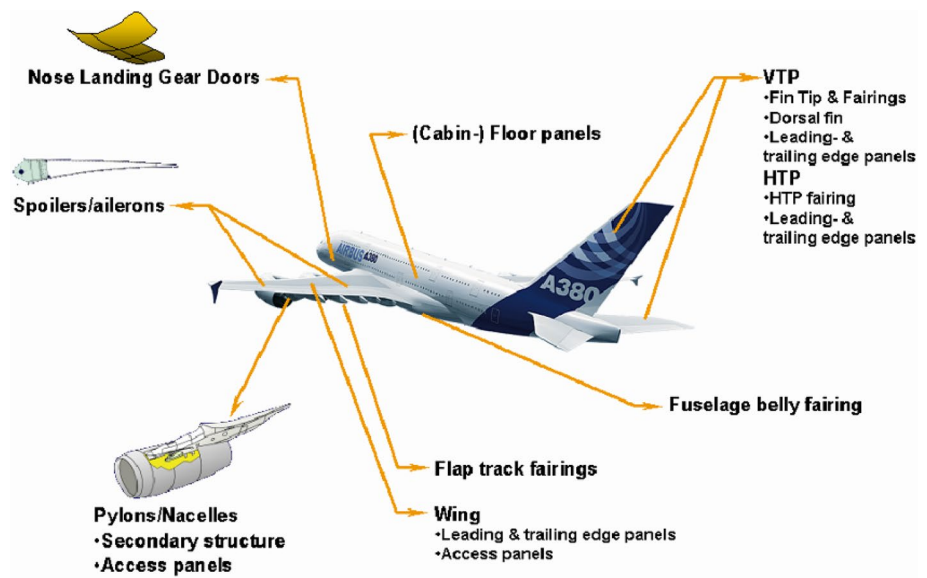


demonstrated repeatable array kinematics devoid of potential failure reasons, and compact packing was achieved as demonstrated in Fig. 34.

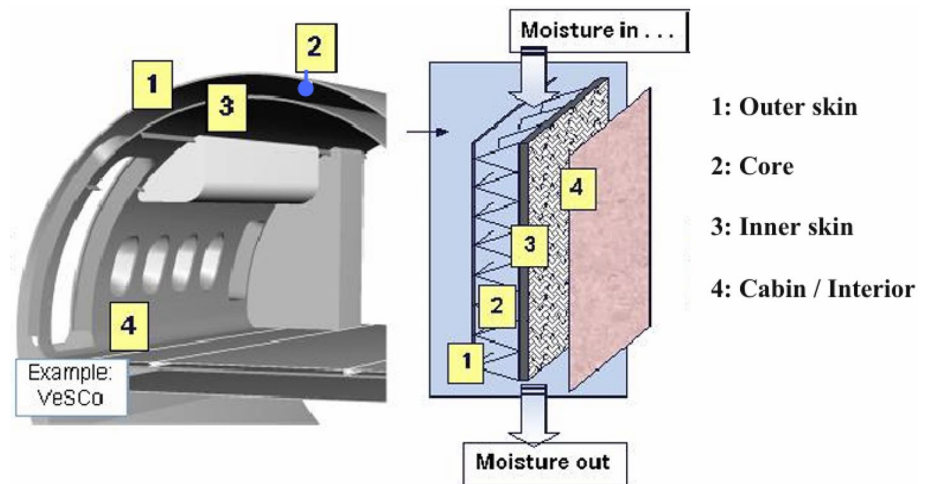
Sandwich structures are used in the aerospace industry to make airplane components including rudders, flaps, and ailerons. To optimize the structure's stiffness at a very low weight, sandwich structures are built using high-strength/stiffness-facing skins or face sheets attached to a lightweight core. Additionally, research has demonstrated that sandwich constructions provide superior acoustical and thermal insulation in addition to increased fatigue strength [124, 125]. This problem has been partially and partially solved in the past and present by the use of longitudinal stiffeners and stabilizing rings with stringers, ribs, or frames in traditional aircraft structural design. However, in the context of composite design, this is not a particularly elegant method. Using twin skins with a stabilizing liquid between them, which forms a barrier to deforming stresses, may often stabilize a surface more successfully [126]. Herrmann et al. [126] also explained the major applications of sandwich structures in aircraft components as shown in Fig. 35. In recent years, a number of companies have examined a number of sandwich designs for composite fuselage. The integrated double shell design (IDS), which enables the integration of several functions into fewer components, is created via research. Ventable Shear Cores, or VeSCo, is one of the ideas that is presently being investigated and improved. Figure 36 diagrammatically illustrates the VeSCo idea. With the goal of minimizing weight loss without sacrificing stylish protection from noise and damage, VeSCo was created. The aerodynamic surface is again provided by the outer layer. A core material, which is ventable to prevent moisture buildup, is sandwiched between the two skins [126].

The fast advancement of space technology has led to an increase in the size and complexity of spacecraft construction and operation, as well as other spatial systems that mostly consist of trusses. Traditional ground manufacturing

**Fig. 35** Sandwich structure application examples (A380) [126]



**Fig. 36** VeSCo idea (shown graphically) [126]



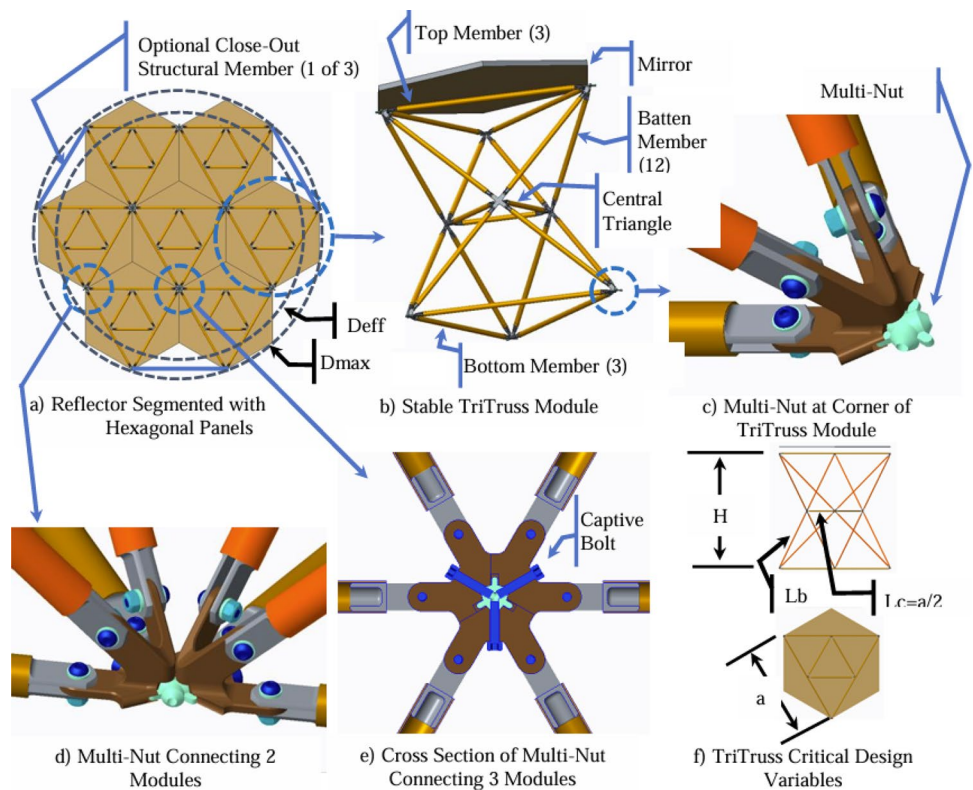
integration approaches have drawbacks that have been brought to light by design and launch cost constraints [127]. Future permanent missions, such as in-space established telescopes and scientific and communications platforms, will be based on modular structures that may be erected on-orbit. Researchers at the NASA Langley Research Center have designed a novel structural module called TriTruss Fig. 37 for use in platforms and telescope applications [128]. For instance, in-space assembled telescopes (iSTA) [129] that shown in Fig. 38.

Recently, a great deal of effort has gone into creating robots with the ability to move and see in areas that are too small for humans to access, such as sewage pipes and the tiny spaces between buildings. Therefore, Ariga et al. [22] proposed a breakthrough wall climbing robot that can navigate vertical tight places, with a special emphasis on the narrow gap between two walls as shown in Fig. 39. The two driving modules that make up this robot include a pantograph in the middle that provides a pushing force against the walls to keep it from collapsing. The pantograph is equipped with two distinct types of springs to guarantee a predetermined amount of pushing force.

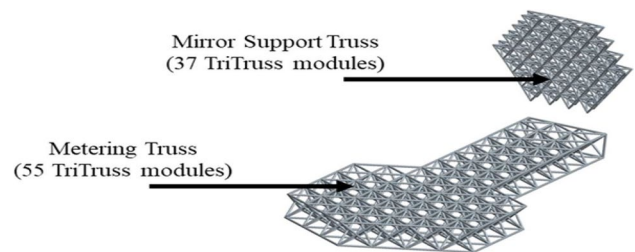
Sprowitz et al. [130] presented the Oncilla robot, a four-legged mobile device (Fig. 40). This unique, 5.1 kg, large-cat-sized robot is a member of a new family of autonomously walking, bioinspired, legged robots. In order to adjust for predefined body and leg postures during turning maneuvers, outdoor mobility, and ascending and descending slopes, the pantographic leg design is spring-loaded. The idea is based on how three-segmented animal legs' parallel the positioning of the proximal and distal limb segments when walking. Moreover, A jumping locomotion system based on a multi-stable tensegrity structure is developed and described by Schorr et al. [131]. By transforming strain energy into kinetic energy, a change in the equilibrium configuration of the tensegrity structure triggers the



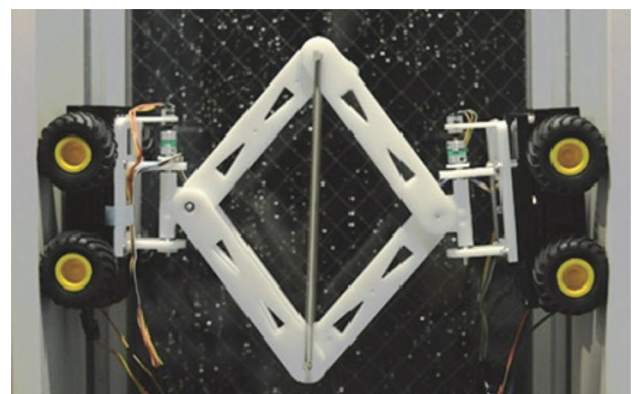
**Fig. 37** TriTruss module specification, geometry, and multi-nut metallic connection [128]



**Fig. 38** The foundational truss structure of an in-space assembled telescope (iSTA) [129]

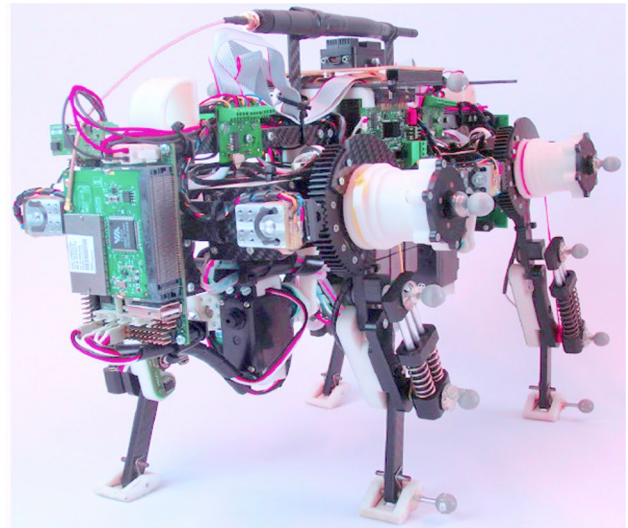


**Fig. 39** An overview of the developed robotic wall climber [22]

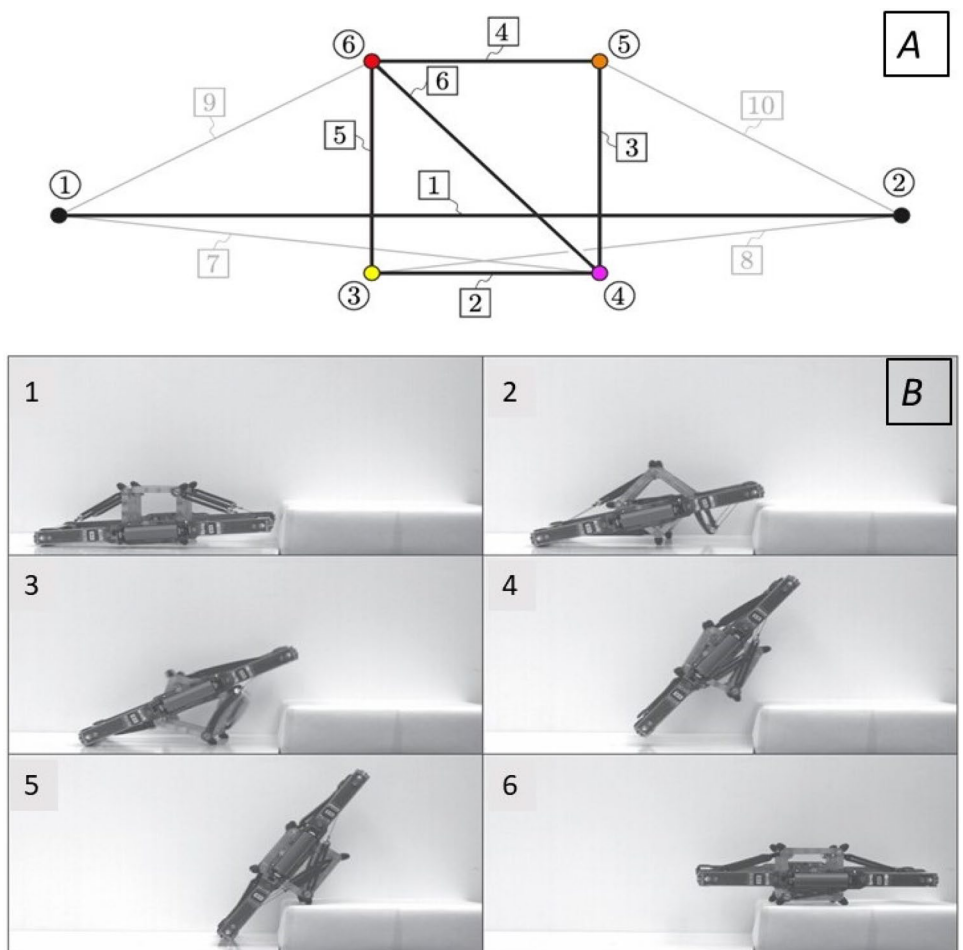


locomotion system to initiate movement. In the given structural topology in Fig. 41A, the members  $j = 1, 2, \dots, 6$  are compressed members and the members  $7, 8, \dots, 10$  are tensioned members. Figure 41B illustrates the addition of a 40 mm-tall step to the experimental setup. Consequently, the multi-stable tensegrity prototype is used to objectively validate the leap over a gap. Additionally, the accompanying actuation mechanism is straightforward, and the stress resistance of the tensegrity reduces damage to the actuator and structure (Fig. 42).

**Fig. 40** An image of an oncilla quadruple robot from an isometric perspective [130]



**Fig. 41 A** The examined tensegrity structural topology is represented by a two-dimensional model with ten segments connected by six nodes [131], **B** several stages of the prototype’s jumping accessibility on one of the steps [131]



## 4.2 Civil engineering and architecture

Engineers and architects are lifelong learners who are always evolving. They produce unique spaces, shapes, and structures. Lightweight constructions come in a variety of shapes, sizes, and uses. These structures have changed



**Fig. 42** An overview of the cantilever truss bridge [136]

throughout time and will keep changing as technology and material engineering develop. Lightweight buildings can be supported, large or tiny, permanent or temporary, indoors or out, and so forth [5]. Several engineering disciplines must be integrated into new product development procedures for structural design to be successful. The topics include materials engineering, mechanical engineering, and civil engineering [118]. The use of lightweight structures in architecture and civil engineering has improved recently. In addition to being socially conscious and materially economical, lightweight constructions also enhance architecture. They need careful planning and production, which creates jobs [132].

Recently, there has been an improvement in the usage of lightweight structures in civil engineering and architecture. Lightweight buildings not only save resources and are socially responsible, but they also improve architecture. They need meticulous planning and manufacturing, which generates employment [133]. During the late nineteenth century, several steel truss bridges (Fig. 42) were built in the US [134]. Pin-ended solid bars were utilized as tension members in light-class trusses, while small rolling forms were used as compression members. The connections of the tension members were mechanically hinged by means of a large pin located at the forged ends of solid bars [135].

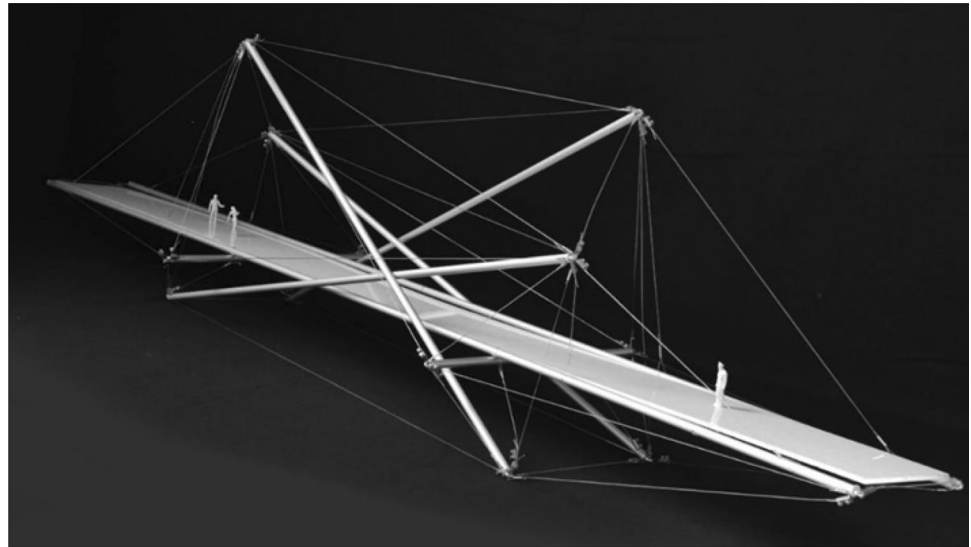
A challenging optimization problem persists in determining the range of viability for tensegrity (foot) bridges based on structural performances like stiffness and self-weight because nonlinear calculations are required and there are many parameters that define these kinds of structures, including topology, span, width, height, cross-section dimensions, material properties, prestress, and external loads. But as seen, these intricate components may be utilized in the building of bridges Fig. 43 [137]. Figures 44 and 45 show physical models of tension bridges by Shawkat [5], highlighting the connection between structural engineering and art. It is possible to clearly see all forces in lightweight constructions. Engineers size structures based on forces that are easily observed.

Prehistoric people first came up with the idea of using a rope, chain, or cable to suspend weights over a barrier. But it wasn't until 1823 in Geneva when Frenchman Marc Seguin, one of five brothers who constructed hundreds

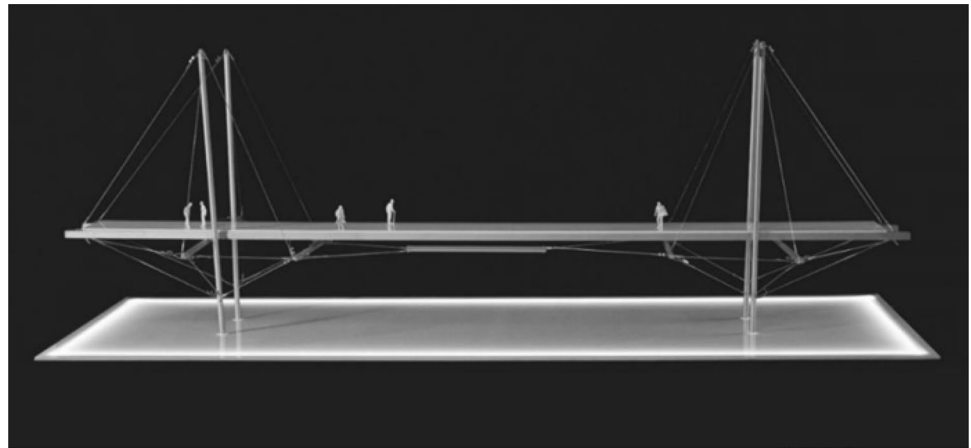
**Fig. 43** Kurilpa Bridge (2009, Brisbane, Australia) designed by Cox Rayner Architects and Arup [137]



**Fig. 44** Pedestrian tensegrity bridge [5]



**Fig. 45** Pedestrian tensegrity cable-stayed bridge [5]

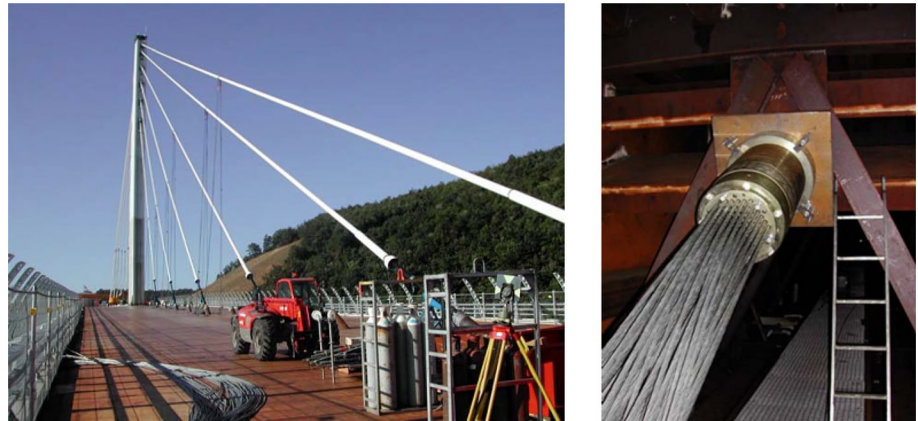


**Fig. 46** Friedrich Ebert Bridge across the Rhine at Bonn (Germany) [138]



of suspension bridges around Europe over the next 20 years, produced the first ever permanent bridge held up by pulled iron wire cables. Despite their modest sizes, each of these bridges served as an essential forerunner to the more imposing constructions that came after [138]. There is a growing trend of building megastructures with enormous spans, such as cable-stayed bridges [139]. Cable-stayed bridges in Fig. 46, are classic examples of modern infrastructure because of their distinctive design and engineering. Cable and tower design principles, along with advancements in building materials, allow these structures to reach unparalleled heights, both physically and metaphorically [140]. Stay cables in Fig. 47, one of the most significant force-transmitting elements of contemporary cable-stayed bridges, are essential for expressing the dynamic qualities and overall stability of the bridge system [141, 142].

**Fig. 47** General view of cables and an anchorage inside the deck [143]



**Fig. 48** Lillebælt suspension bridge (Denmark) [138]

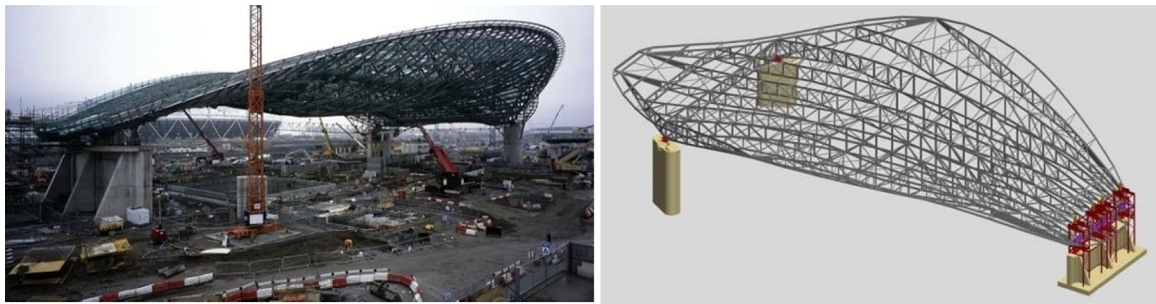


**Fig. 49** Mono-, bi- and tri-cable ropeways [145]

A suspension bridge (Fig. 48) is a kind of bridge where the deck is suspended on vertical suspenders underneath suspension cables. Early in the nineteenth century, this kind of bridge was constructed for the first time in contemporary times. There is a long history of simple suspension bridges in many hilly regions of the world, which do not feature vertical suspenders. The suspension cables must be fastened at both ends as any weight applied to the bridge causes stress in these main cables. The main cables pass through the pillars, support the deck, and link to anchors buried in the ground [144].

Additionally, cables are used in cable car construction. Popular aerial ropeways, often called cableways, are useful forms of transportation in challenging environments, particularly in mountainous areas. They are mostly used to take locals and visitors to ski resorts as a kind of public transportation. Since there might be a large range of structural systems in an actual cableway design (Fig. 49 Mono-, bi- and tri-cable ropeways [145]), the identification criterion determines how these systems are classified. While there are many factors that may be considered, the two primary ones are the kind of motion and the quantity and purpose of the ropes [145].

Globally, there has been a growing interest in space frame structures during the past 50 years as shown in Fig. 50. The main objective of engineers and architects has always been to develop novel structural shapes that can manage enormous, open spaces. As new building techniques and materials are developed, spaceframes often provide the best answer and meet the requirements for speedy, lightweight, and economical construction [146]. Space structures are stunning structures constructed in prosperous countries for the purpose of enticing tourists [147]. These dynamic,



**Fig. 50** The space frame construction is supported by an RC wall and RC columns [151]

lightweight structural systems find use in a wide range of structural contexts. For example, they serve as structural coverings for huge spaces like concert halls, exhibition halls, and stadiums. They fit the architectural standards and have a nice appearance [148]. Space structures stand out due to their lightweight, low cost, and speedy erection. For instance, due to their structural effectiveness, spatial structures are intended for claims like wide-span roof structures or deployable mesh reflectors [149, 150].

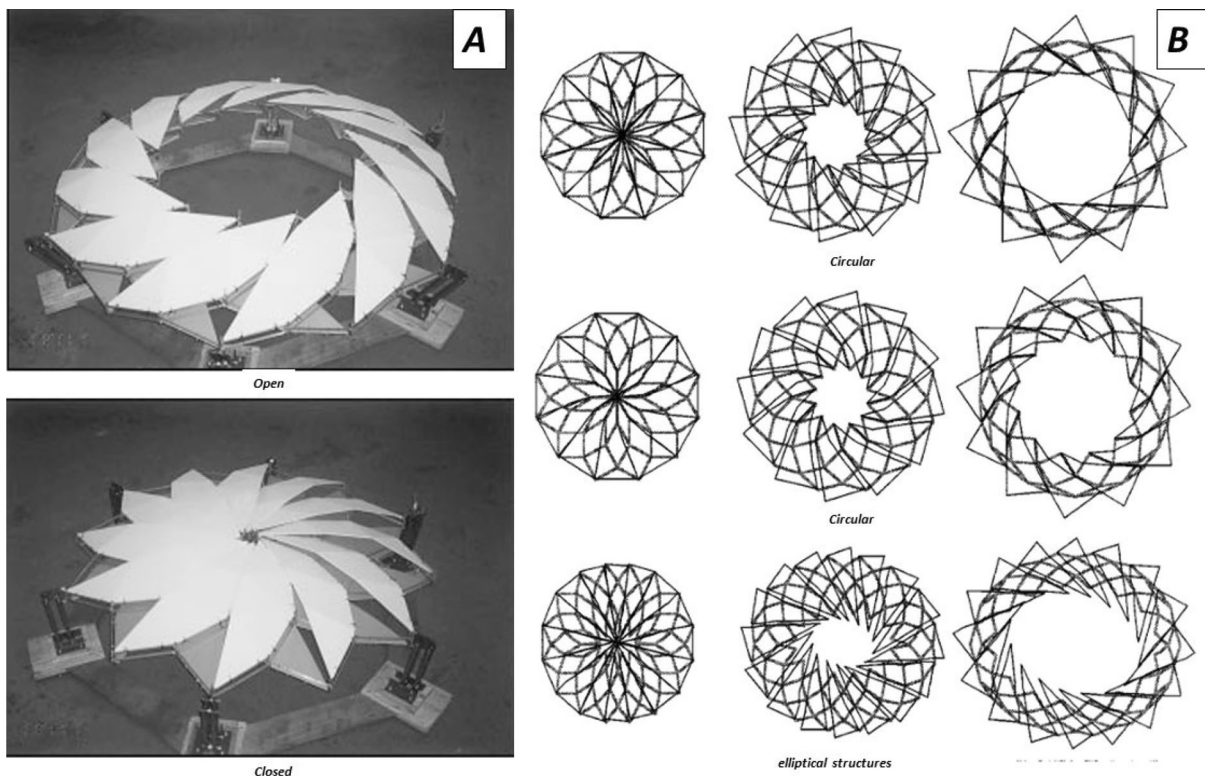
One of the most popular forms of entertainment attractions is Ferris wheel constructions, which are particularly popular in business areas with picturesque surroundings and uses of various lightweight structural types like trusses and cables. The Ferris wheel construction consists of a spinning wheel, several passenger-carrying cabins, and a support structure. The Ferris wheel may exert a significant lateral and vertical load on the support system. The P-delta contribution from the vertical load would significantly increase the lateral-load effect, making it crucial to the structural behavior. In order to improve global stability, an effective lateral-load transfer mechanism is necessary for the design of a cost-effective support system. As such, it is possible to distinguish between two main types of Ferris wheel support systems. The first kind uses a truss mechanism to transfer lateral loads in an A-shaped column structure [152] as shown in Fig. 51. The second kind is a braced support system with a pre-tensioned cable that transfers lateral loads using a pre-tensioned cable system as shown in Singapore Flyer in Fig. 52.

The construction of “flexible sports facilities,” which may be used year-round under “optimal conditions,” or with the roof open for as long as the weather permits, is becoming more and more dependent on retractable roofs as shown in Fig. 53A. This calls for roofs that can be quickly opened and closed with a single button push in a matter of minutes [155]. Many ideas for large-span retractable roof constructions have been put out in the past 20 years, and some of these have been successfully implemented in sports stadium roofs to handle significant events like the World Cup, Olympics, and Professional Tennis Tour. Among these ideas is a novel kind of retractable construction that employs fundamental structural elements like angulated scissors [156]. Figure 53B explains jointing pantographic units to create retractable structures with different configurations.

**Fig. 51** An A-shaped column system supported London Eye in the assembling process [153]



**Fig. 52** Singapore Flyer during construction, the view to the northwest of Singapore Flyer [154]



**Fig. 53** **A** Deployable roof model courtesy of Taiyo Kogyo in open and closed conditions [155], **B** covering elements for circular and elliptical structures [155]

### 4.3 Medical applications

Scholars investigated applications of different lightweight structures in medical fields as explained in Table 3. Research on biotensegrity describes the structure and function of biological systems using the idea of tensegrity. It

**Table 3** Different medical applications of tensegrity and origami structures

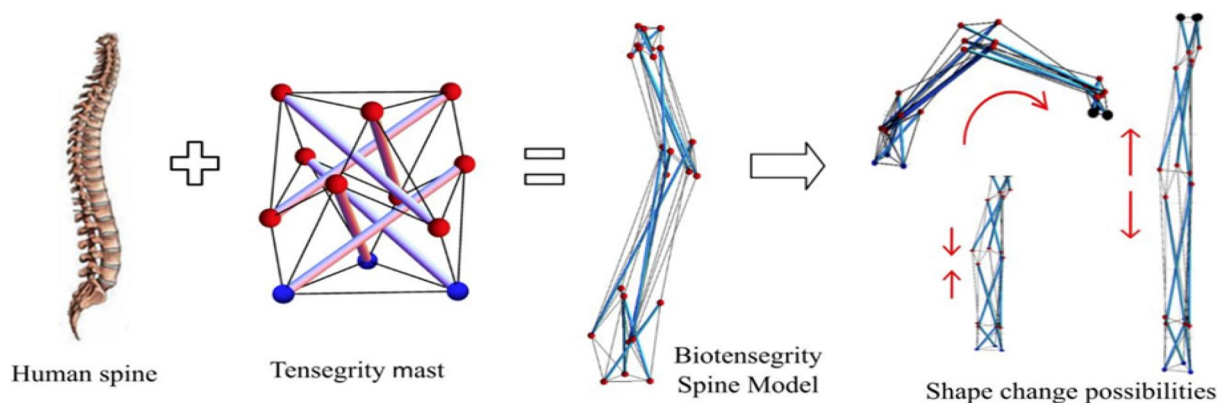
Structure	Application	References
Tensegrity	Spine tensegrity	[157, 158, 162]
	Cranial surgery instrument	[159]
Origami	Surgical retractor	[161]
	Drug delivery	[163]
	Cell and tissue engineering	[163]
	Minimally invasive surgery	[163]

started in the eighties. Biotensegrity is made up of tensional (fascial, muscle, and tendon) and compressive (vertebrae) elements that work together to distribute forces throughout the system, preserve a stable structure, and prestressed during rest [157]. Oh et al. [157] presented a method for assessing the shape change of spine biotensegrity models in many orientations. Spine biotensegrity models are executed in four stages using the shape change method: initial, deformed, shape change, and goal. As a result, monitored nodes are able to travel in the required directions. Another paper examines form-finding for four-stage class one self-equilibrated spine biotensegrity models by Chai Lian et al. [158] (Fig. 54).

During cranial surgery, a mounting and guiding system is employed to ensure that instruments operate inside the appropriate region and angle. One substitute is to include tensegrity structures consisting of wires in continuous tension and bars in continual compression into a steering system, as suggested by Ryan [159] as shown in Fig. 55. Tension causes the triangular tensegrity structure to rotate. With three strings per tensegrity prism, the actuation is inadequate, but the bar combinations enable the necessary positioning.

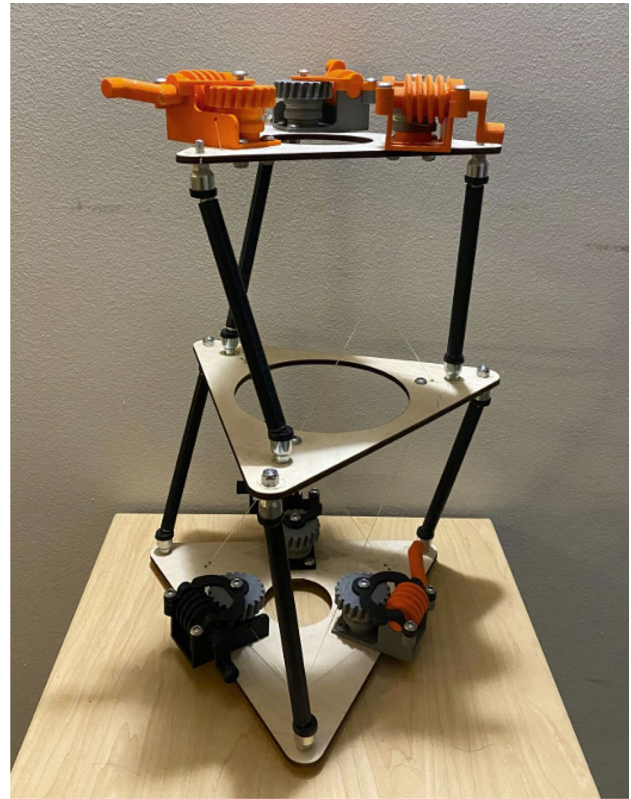
The biomedical industry is a leading research and application field for origami-based technologies. Origami structures have been employed in a variety of biomedical applications, including drug administration, gastrointestinal microsurgery, microfluidic devices, and sterilizers [160]. Origami-based robots are adaptable, obedient, and bio-inspired, making them ideal for medical applications in tight places. Banerjee et al. [161] describe an origami-inspired surgical retractor with an adjustable stiffness mechanism that provides safer instrument-tissue contact than rigid alternatives, the model is shown in Fig. 56.

Metallic implant materials, including stainless steel, titanium, and cobalt-based alloys, have several medicinal uses. These materials are commonly employed to replace human body structural components due to their superior tensile strength, fatigue resistance, and fracture toughness. They are commonly utilized in medical equipment such as artificial joints, dental implants, hearts, bone plates, staples, wires, and stents [164]. Metals are widely employed in biomedical applications, including weight-bearing implants and internal fixation systems [165]. Figure 57 demonstrates the utilization of stainless steel and Co–Cr alloy as implant devices in humans [165]. These applications of lightweight components in medical applications are different from other robotic and automotive applications because they must be in contact with alive cells and tissues and respond in adaptation with other tissues and organs as Teoh [164] explained, implants require interaction with host tissues.

**Fig. 54** The study's motivation by Chai Lian et al. [158]



**Fig. 55** Finished physical prototype assembly of tensegrity structure by Ryan [159]



**Fig. 56** Origami-inspired deployable surgical retractor [161]



**Fig. 57** Stainless steel implants in **a** knee and **b** ankle. **c** Knee replacement made from CoCrMo alloy [165]

## 5 Structural analysis and design

Structural analysis is the study of how a structure responds to external forces such as loads, temperature variations, and support settlements. Structural design is the process of selecting the appropriate member sections, materials, and arrangements to meet the current code of practice standards while also enduring the internal forces (stress results) caused by a certain set of loads [166]. An engineer-designer's primary goals are to create structures that are safe from external effects, adhere to predetermined standards, and have a desired economic impact. Despite being widely used in modern engineering, lightweight structures are vulnerable to several types of deformations [167]. For some time now, researchers have been analyzing structures using numerical methods such as the force technique and stiffness matrix method [168]. Because loadings are more erratic and average project scopes are larger than those of other engineering disciplines, the construction industry frequently operates with a looser tolerance than other engineering disciplines [169]. In the field of structural analysis, numerical methods can be broadly classified into two categories: either the discrete structural elements are idealized into an assembly with an assumed form of stress or displacement distribution, and the complete solution is then obtained by combining these separate, approximate distributions of stress or displacement in a way that satisfies the displacement compatibility and force equilibrium at the junctions of these elements; or the differential equations describing the deflections and/or stresses in the structure are solved by means of numerical computing procedures [170]. The ability of the analyst to realistically idealize the structure is critical to the effectiveness of the direct stiffness approach analysis of practical aircraft constructions. One aspect of the idealization difficulty is selecting appropriate elemental stiffness matrices to appropriately represent the elastic behavior of the structure [171]. Finite element analysis, dynamic relaxation, and, linear and nonlinear force approaches are the most well-known iterative techniques for obtaining an analytical solution [172].

The force method was a popular structural analysis approach used in civil, mechanical, and aeronautical engineering back when computers weren't even invented. Its precision in calculating the forces within the structure is what accounts for its appeal. A thorough investigation of automating the force technique—which includes the computer-assisted creation of compatibility criteria—during the matrix-based structural analysis formulation stage was conducted [173]. Since the properties of members of a structure typically depend on the member forces rather than joint displacements, design engineers find great appeal in the force method to structural analysis, in which the member forces are treated as unknowns [174].

The equations governing the issues encountered in nature may be numerically solved using the Finite Element Method (FEM). Differential equations are often used to describe the overall behavior of nature. Because of this, the mathematical community accepts the FEM as a numerical method for resolving integral or partial differential equations [175]. Due to the difficulty or impossibility of solving the differential equations defining a structure's displacement field analytically, the structural problem's domain can be split up into several tiny subdomains known as finite elements (FE) [176]. In order to calculate airplane constructions, Turner and associates developed the concept of the finite element method (FEM) in 1956 by using pin-jointed bars and triangle plates. The use of FEM in structural engineering, heat transfer, fluid mechanics, aerodynamics, and electrostatics grew in about 1980 with the release of new commercial software packages. Individuals such as Przemieniecki, Zienkiewicz, Cheung, Gallagher, Argyris, and others are credited with the early establishment and advancement of FEM [176].

Dynamic relaxation (DR) has seen substantial evolution during the past 60 years. In order to solve the linear or nonlinear response of governing equations resulting from structural analysis, these explicit and iterative approaches are commonly employed [177]. The foundation of the dynamic relaxation technique is the notion that a system experiencing damped vibration eventually settles in the static equilibrium's displaced location. When a constant external force is applied to the system to excite it, dampened vibration begins. Math and physics may be used to understand the process. The process is analogous to figuring out a dynamic system's steady-state solution in terms of mechanics [178].

There are great efforts in designing lightweight structures through optimization. Structural optimization is the methodical process of identifying a structural design that, given a goal and a set of geometrical and/or behavioral constraints, is the best of all conceivable designs [179]. The reduction of superfluous material progressively results in the optimal shape of a structure. This is the fundamental concept of evolutionary structural optimization. A structure may be subject to certain design restrictions, including those pertaining to stiffness, frequency, and buckling stress. To reduce content, various rejection criteria must be used, based on the types of design constraints [180]. In [14], the feasibility of strategically positioning extra members in space structures to reduce the bending moment in key

members was investigated. Instead of expanding the members to resist the extra loading. In prestressed truss structures, the quantity and number of actuators were decreased by Manguri et al. [181] using optimization algorithms and force method regulating equations. Among these were the sequential quadratic programming (SQP), trust-region-reflective, interior-point, SQP heritage, and active-set optimization techniques. The ideal mass-to-stiffness ratio in tensegrity structures is the main topic of [182]. To provide the best designs under various loading situations, the method begins with an initial layout that shows the maximum number of permitted element connections and looks for the structure's topology, geometry, and pre-stress. In another study, [183] offered a free-form optimization technique for cable-membrane structure design that discovers the shape and maximizes stiffness. Based on the H1 gradient approach, the suggested free-form optimization strategy is a type of non-parametric optimization methodology. Moreover, in order to build the least weight deploying pantograph structures while adhering to code-based design specifications and kinematic limitations, Thrall et al. [184] suggested a structural optimization approach. The form and size optimization subproblems are iterated using a layered method. More on Pantographs, [98] presented a novel approach to accurately regulate nodal displacements in pantographic systems. The Matrix Condensation of Force technique, which is the foundation of the approach, seamlessly integrates with the Interior Point Optimization methodology.

There are many software used widely in the analysis and design of lightweight structures. For example, MATLAB software was used by Manguri et al. [185] in the computational optimization of bar size in single-layer dome structures and by Saeed [186] for controlling displacement in pin-jointed assemblies regarding the optimization techniques. Furthermore, Manguri et al. [98] implemented SAP2000 software to compare results with MATLAB in their work on displacement control of pantographic structures using matrix condensation with interior point optimization. While Sangeetha et al. [187] analyzed space truss structures with varying cross-sectional areas of members, support conditions, and influencing design parameters using ANSYS software. Also, Mohamad [188] developed a truss finite element analysis using ANSYS software. Moreover, ETABS software is used in the investigation of reliability analysis of space truss structures [188]. In addition, Szczepanski et al. [66] analyzed the natural frequency of wood structures using DLUBAL RFEM software. On the other hand, Nariman et al. [189] used ABAQUS software to simulate the response of a cable suspension bridge under wind load.

Lightweight structures' mechanical properties and failure mechanisms under dynamic stress differ significantly from those under static loads, which affects how these structures are used and developed in the aerospace and automotive industries. Because of their strain rate sensitivity, materials frequently appear stronger and more rigid under dynamic stress. Additionally, it enhances their energy absorption and dampening capabilities, which are critical for controlling vibration and impacts. Dynamic stresses can accelerate fatigue failure, and materials that exhibit ductile behavior under static pressures may fracture brittly under dynamic conditions. These factors necessitate careful material selection—high-strength alloys and advanced composites are preferred—as well as structural optimization to guarantee effective energy absorption and distribution. Designs must incorporate components that increase crash-worthiness and fatigue resistance, which calls for rigorous testing. Therefore, knowledge of the dynamic behavior of materials is needed to design lightweight structures that meet the stringent performance and safety criteria of aerospace and automotive applications.

A significant number of research has been conducted on structural design ranging from rigid, rigid-flexible, to flexible structures, with performance analysis comprising static loads, structural stability, and dynamics [190]. Up till now, contemporary structural design principles have evolved. The damage tolerance method serves as the foundation for the predominant design philosophy in use today [118]. In many lightweight bar structures such as trusses, members that carry axial stresses in static modes may fail due to yielding (tension or compression) or buckling (compression members) [191]. Once a tension part yields during dynamic stress, strain hardening may cause it to take on extra load [192], in contrast to a buckled compressive member, which weakens and transfers weight to other components [193].

On airplanes, loads are frequently dynamic and may be divided into two categories: limit loads and ultimate loads. Limit loads are frequently only maneuvering and gust loads that fall inside the typical flying envelope. The structure must sustain ultimate loads, which include crash loads and specific kinds of damage that are allowed to the structure, for a short period of time. Considerations for dynamic loads may include fluid dynamics, vibration, force, momentum, and collision [194]. In aerospace engineering, since the inception of aviation, aircraft and the aerospace sector have placed a high premium on flight safety and failure analysis has been widely used in investigations throughout the years into events related to flight safety and aviation accidents and incidents [195]. The failure analyses yield other valuable information in addition to the failure sequence based on the beginning parameters [194].

## 6 Conclusions

This study's primary focus is on the creation and use of lightweight structures in the field of structural engineering. The idea behind the lightweight design is, that better outcomes can be achieved with lighter equipment, this is particularly true for rapidly accelerating cars, airplanes, and smart structures. After a detailed investigation, the following conclusions are drawn:

- The aircraft sector was a pioneer in lightweight engineering. The aerospace and automotive industries have pushed for innovative structural lightweight materials in an effort to lower the weight of cars and aircraft, improve energy efficiency, and satisfy strict functional criteria.
- Materials like magnesium, fiber-reinforced polymers, titanium alloys, shape memory alloys, Ceramic Matrix Composites (CMC), and aluminum alloys have all been essential to the creation of lightweight structures.
- The progress of technology such as deployable and morphing structures, 3D printing, advanced joining technologies, embedded sensors, and actuators have a great role in advancing applications of lightweight structures in different forms.
- Numerous lightweight structure types are under the umbrella of structural engineering, and they may be categorized according to the materials they are made of, how they are shaped, and the forces acting on their individual components. For Instance, truss, pantograph, tensegrity, cable structures, origami, and sandwich structures.
- With the right methods, lightweight materials and numerically optimized structures may be built to create lightweight aeronautical systems and components.
- There are applications in aerospace and robotics such as in telescopes, aerofoil and airplane structures, civil structures, and architecture such as bridges, retractable roofs, cable cars, and medical equipment depending on the application of structural mechanics.
- There is rapid growth in developing new analysis techniques, optimization methods, and software applications in advancing the field of lightweight structures.

## 7 Perspective and recommendations

Scientists have a strong motivation to advance the design and use of lightweight structures for humankind's future, by assisting the environment and protecting it from other hazardous construction materials and systems, as well as facilitating human activity through various developments in lightweight structures and technology applications. This procedure is dependent on optimization techniques and developments in lightweight design materials. Structural design and construction based on reuse saves waste, consumes less energy, and does not involve the acquisition of new materials [196]. As the industrial and technology sectors grow, energy efficiency and sustainability are becoming increasingly valued. The aforementioned goals are enacted by the people and then enforced by different government entities through more stringent legal systems. The ultimate goal is to mitigate current environmental damage while also laying the groundwork for efficient and sustainable growth [24]. Nowadays, many challenges in lightweight structures innovations can be seen and can be concluded in:

- In an environmental perspective, there are applications to designing lightweight structures through the reuse of elements. Scholars presented approaches for structural optimization in the design of truss structures through reuse [196]. An overview of the usage of lightweight, reusable materials in temporary constructions is provided by Blomqvist et al. [197]. Herrmann et al. [1] explained that lighter objects can reduce life cycle costs as well since they function on less energy in many applications. Less material used in a particular circumstance can result in lower material and production costs, whereas more embodied energies and inventive but relatively inefficient manufacturing procedures might lead to higher prices.
- Over time, advancements in lightweight structural design have increased efficiency, dependability, and safety, particularly in civil aeronautical projects. Both newer designs and older aircraft must now demonstrate damage tolerance in order to remain airworthy. In order to keep airworthiness, scheduled routine inspections that call for teardowns are now required [118]. The current revolution taking place in the commercial aircraft production busi-

ness may be summed up in composites. The desire of airlines and aircraft manufacturers to include composites in their fleets is motivated by several valid factors. Since many composite materials are stronger than traditional metallic materials, the aircraft's weight and, thus, the fuel cost per passenger carried, are decreased [198].

- Single or composite materials are used to create smart constructions. The characteristics of the material have been improved by the use of nanotechnology. The appropriate applications of contemporary technology include structural components, coating or protective elements, and monitoring elements [199]. Moreover, Carbon fiber-reinforced composites are already seeing an increase in use, particularly in lightweight applications that the aviation industry sorely needs. The principal driving force behind this growth, and specifically the increasing use of epoxy-based thermosetting composite materials in the construction of aircraft structural elements, is the significant weight reduction that can be achieved while preserving a competitive advantage over traditional metallic alloys concerning resistance to fatigue and corrosion damage [200].

However, the future of lightweight design needs further investigation to mitigate the sustainability and also performance required in the field, for example:

- Increasing the awareness of using mobile structures instead of conventional structures in order to further apply lightweight structures in future applications including, daily life activities, aerospace explorations, and technological innovations.
- Further investigations in lightweight materials are needed in order to meet goals in eco-friendly applications and also improve the performance of these types of structures with a weight reduction.
- Further explorations in structural optimization techniques as a primary concept-based design of lightweight structures and applications of proposed results from scholars in this field.
- Inventing better joining technologies that can help assemble lightweight members in easier and faster ways will be a positive point in wider applications of these structures especially in truss, tensegrity, and pantographic structures.

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**Data availability** No datasets were generated or analysed during the current study.

## Declarations

**Competing interests** The authors declare no competing interests.

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