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Skeletal Space Structure Systems: Select Areas of Opportunity to Achieve Sustainability in Construction

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Abstract: This paper examines some of the largely neglected areas of opportunity to utilize skeletal space structure systems in support of the modular, industrialized, economical, sustainable, and digital future of the construction industry. In this context, the feasibility of the future use of skeletal space structures is studied for a few classes of engineering structures, namely, residential apartment buildings and offshore platforms, along with their suitability for the reconstruction, renovation, modernization, and retrofit of damaged buildings and urban areas of cultural heritage significance. Finally, the particular features of lean project management in space structures are discussed with emphasis on engineering and economic factors, production management, environmental aspects, quality management, reliability, maintainability, and sustainability. This article concludes that skeletal space structures can fulfil many of the essential construction requirements of modern societies, especially those facing environmental challenges, all while allowing for design flexibility and mass customization.

Keywords: space structure systems; composite structures; double- and single-layer grid structures; sustainability in design; mass customization; kit of parts; digital engineering and construction

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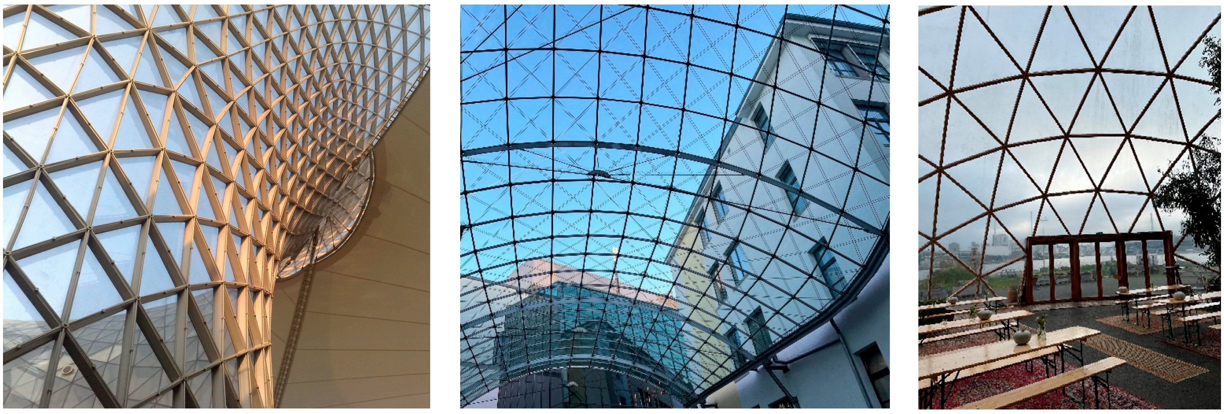
1. Skeletal Space Structure Systems

Skeletal space structure systems are modular, kit-of-parts-ready [1] solutions comprising a combination of spatial frames and trusses that may be arranged in various formations, such as double- and triple-layer grids, braced barrel vaults, and braced domes. Initial advancements in the theory and practice of skeletal space structures have been well documented by Makowski [2,3], and the pioneering work of the Space Structures Research Centre of the University of Surrey [4]. These systems are lightweight, suitable for fast and easy fabrication/erection/dissembling, and scalable to promote economic mass production and industrialization. Originally, skeletal space structure systems were used predominantly as roof structures—particularly where large spans with load distribution in both perpendicular directions were desired—to satisfy the basic demands for fast and economical reconstruction and redevelopment after World War II. Later, due to changing construction demands, and with the advent of new materials [5] (e.g., wood dome; Figure 1c), construction techniques [6] (e.g., free-form botanic garden; Figure 1a), and computational engineering approaches [1] (free-form roof modules; Figure 1b), many architectural and engineering practitioners concentrated on creating innovative and geometrically custom space structural forms for attractive and free-form monumental buildings [7]. As such, in addition to the customary use of modular space structures for mass production, skeletal space structure systems can be utilized to design custom structures in terms of shape, geometry, and characteristics. These established applications demonstrate that skeletal space structure systems are prime candidates for mass customization [8], with design flexibility to tackle a variety of societal demands.



(**a**) (**b**) (**c**)

Figure 1. Examples of skeletal space structure systems: (**a**) free-form botanic garden (China); (**b**) free-form roof structure (Germany); (**c**) geodesic dome (Denmark).

Today, with the sudden incline in costs of construction [9], the localized shortage of skilled labour, limitations in energy reserves, and concerns over climate change [10], the construction industry requires fast, economical, energy-efficient, low-carbon, and preferably locally source solutions, particularly through industrialization, modularization, and mass customization strategies. In particular, given the correlation between the reduction in construction materials with embodied carbon and energy [11–14], the lightweight nature of skeletal spatial structure systems may help foster sustainability through design. To this end, in this study, the potentialities of skeletal space structure systems in largely disregarded and vast areas of suitable applications were examined. In this context, the feasibility of future large-scale use of skeletal space structures was studied for three classes of engineering structures, namely, residential buildings, and offshore platforms, along with their applications in the rehabilitation, renovation, modernization, and reconstruction of existing facilities, including cultural heritage buildings. This study presents the new areas of application of skeletal spatial structures, which had not been presented in previous research, aside from a few studies [15–20], particularly in terms of their potential to foster construction sustainability through design. It will be shown here that, by prioritizing safety, functionality, performance, durability, maintainability, sustainability, cost-effectiveness, ease of construction, and construction quality in conjunction with aesthetics, skeletal space structures may be employed to meet many of the fundamental needs of contemporary societies experiencing environmental issues, without sacrificing design flexibility and customization.

2. Select Areas of Opportunity Using Skeletal Spatial Structure Systems

Many innovative free-form space grids have been built that have proven their virtually unlimited capabilities for creating fascinating structures of unique character (see Figure 1a,b). Here, three new and overlooked areas of application of space grids are discussed, for which the structural forms are modular in nature. This modularization not only offers the benefits of prefabricated mass production and customization for efficient erection and dissembling but also provides suitable bases to form repeating patterns in the corresponding structural stiffness matrices. Hence, by devising suitable numerical approaches, their analysis procedures become extremely easy and numerically stable (see Maalek [15,21] for more details).

The three new areas of application discussed in this manuscript are (i) low-to-medium-rise steel space frame buildings; (ii) offshore steel jackets, including offshore wind turbine supports; and (iii) the reconstruction of geometrically significant heritage dome structures. The application of spatial grids in bridge decks of composite double-layer steel grids and reinforced concrete is discussed in a separate manuscript. Each application area is discussed, and its structural performance is compared with a common construction type as a basis/benchmark for comparison. Moreover, important considerations and discussions pertaining to different factors, such as sustainability, management, production, inspection, health monitoring, architectural significance, and aesthetics are provided. A summary of the applications and the presented analysis and discussions are given in Table 1.

Table 1. Summary of experiments, analysis, and discussions.

Considered Application Areas		Type of Analysis	Benchmark for Comparison	Further Considerations and Discussions
Low-to-medium-rise buildings	• One- and three-storey single-span structures • Three- and five-storey structures	• Seismic nonlinear analysis • Material consumption	• Moment frame • Braced frame	• Architectural design • Structural and seismic response • Mass production economics • Inspection, health monitoring, and safety • Sustainability and resilience
Offshore jacket structures		• Static and dynamic nonlinear analysis • Material consumption	Completed project in the Persian Gulf	• Structural behaviour • Economy of design and construction • Fatigue analysis • Sustainability
Reconstruction of cultural heritage dome structures		Seismic Behaviour Analysis	• Bam earthquake • Reconstruction for the damaged city by earthquake	• Feasibility of reconstruction and retrofit • Economic considerations • Reliability under severe earthquakes • Seismic buckling • Local failure • Sustainability

2.1. *Low-to-Medium-Rise Apartment Buildings*

The considerable rigidity and the low weight of double-layer space grids exhibit a high potential for their use in residential, administrative, educational, and commercial buildings and hospitals. Such buildings are normally constructed with steel moment frames, braced frames, or reinforced concrete frames with or without shear walls. Here, a benchmark building is considered a building with a steel-braced frame, as shown in Figure 2a. In the proposed space grid system, floors are considered to be double-layer grids in composite action with reinforced concrete topping, and walls are fully (Figure 2b) or partially (Figure 2c) built from double-layer grids, tailored for mass production and geometric and size customization. The high redundancies of such systems lead to their high reliability against progressive collapse, and their relatively extremely lightweight and controllable ductility are key factors that distinguish them from many other customary types of building construction. Only perimeter walls are needed, and for structures up to the normal size of such buildings, floors can be designed such that no internal or intermediate columns are required. Openings in walls and floors can hence be provided with no difficulties. A variety of suitable claddings and methods of insulation are available that can be utilized. These provide invaluable freedom of design and functionality for architects, along with support for low-energy and passive housing. To begin with, schematic views of a simple single-storey and an analogous three-storey building composed of double-layer grid floors and perimeter walls are shown in Figure 2d,e, respectively.

2.1.1. Single-Storey Building: Benchmark Experiment Setup

First, some of the basic characteristics of such systems were investigated through simple examples with an emphasis on their seismic behaviour. Consider a $7.6 \times 7.6 \times 3.5$ m^3 single-storey space structure, as shown in Figure 2a. The roof grid layers were set at 500 mm apart, and the centre-on-centre distance of the grid layers of walls was 300 mm. Using an elastic design approach (e.g., [22]), we designed a space grid consisting of modular pyramidal units as well as two types of moment frame structures, one with an internal column and one without any internal columns, as reference benchmark design. Obviously, for larger spans, the omission of internal columns in the moment frame system (the reference benchmark) may not be feasible.

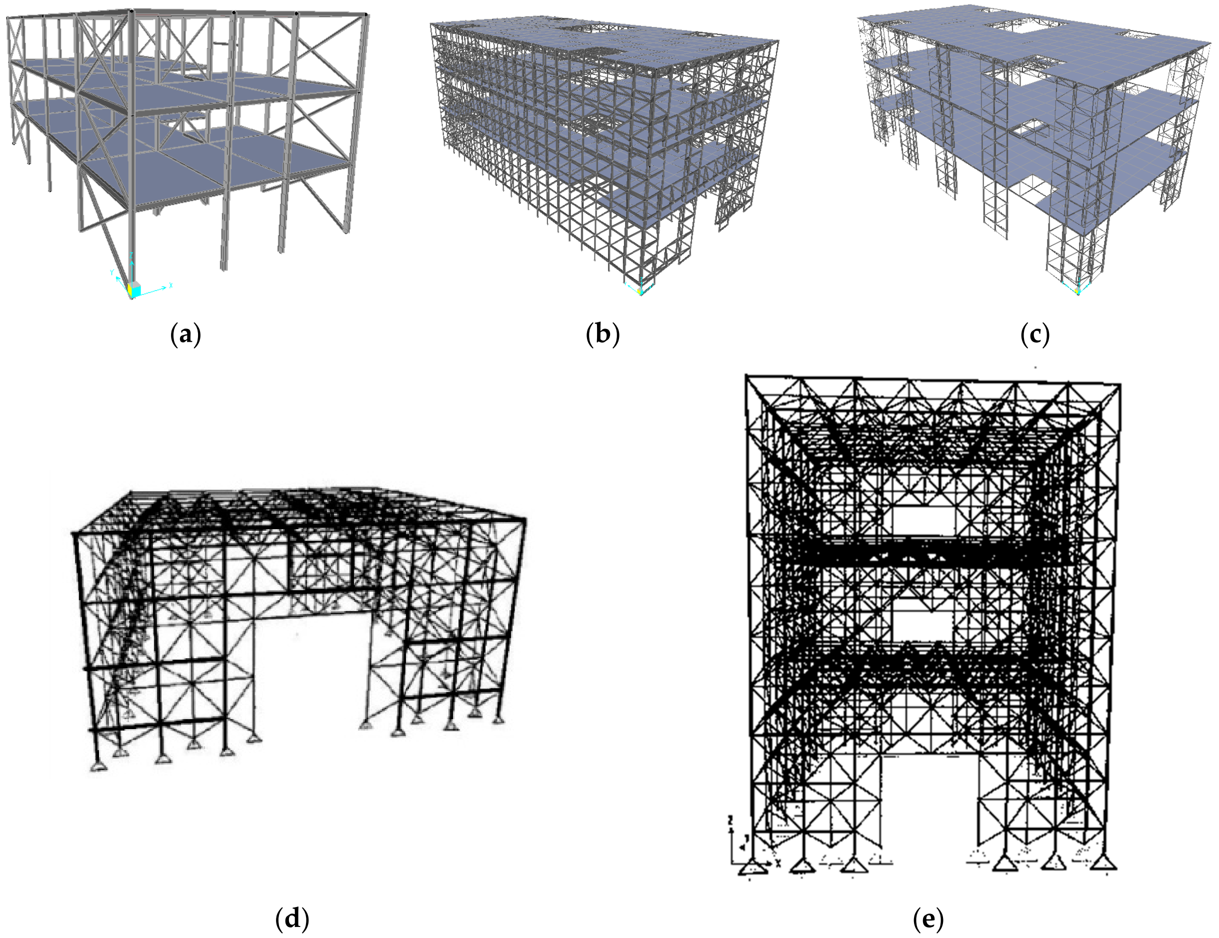


Figure 2. Different 3D models of residential buildings: (**a**) benchmark building; (**b**) proposed fully double-layer grid spatial structure system; (**c**) proposed partially double-layer grid system; (**d**) single-storey analytical structural model; (**e**) multi-storey (three-storey) analytical structural model.

2.1.2. Single-Storey Building: Seismic Behaviour Compared with Benchmark

The result of a pushover analysis for the space frame system with the imposition of certain limitations on the slenderness ratios for certain members at the corners (vertical and diagonal members) resulted not only in 37% less structural steel weight but also 2.5 times higher ultimate strength than the moment frame. In fact, preventing buckling is crucial in achieving a balanced system with high resistance and rigidity as well as acceptable ductility. Furthermore, we limited the slenderness ratios for all floor members to 90, all vertical wall members to 60, and diagonal wall members to 50. This structure responded without a sign of failure during nonlinear dynamic analysis under simultaneous applications of the time history of three translational components of the earthquake recorded at Altadena (from the United States Geological Survey) with the peak ground acceleration magnified to gravitational acceleration (i.e., 1.0 g), as shown in Figure 3a–c. The lateral load–lateral displacement relationships resulting from a pushover analysis (Figure 3d) reveal that a desirable ductility can be achieved in design by preventing failure through member buckling, the brittle fracture of connection bolts, and other modes of failure.

In Figure 3, the results presented with thicker and thinner lines correspond to the compression member behaviour based on FEMA 365 [23].

2.1.3. Three-Storey Building: Seismic Behaviour Compared with Benchmark

As another example, we considered a three-storey apartment building with double-layer composite grids as floors and double-layer grids provided partially to act as both load-bearing walls and a lateral load-resistant system (Figure 2b). The plan dimensions of this system were designed as 22 m by 11 m. To compare the above model with the corresponding moment and braced framed models, the common practice in the design of such buildings with internal columns was considered. Hence, our moment-resisting frame model had four internal columns, which limits architectural freedom.

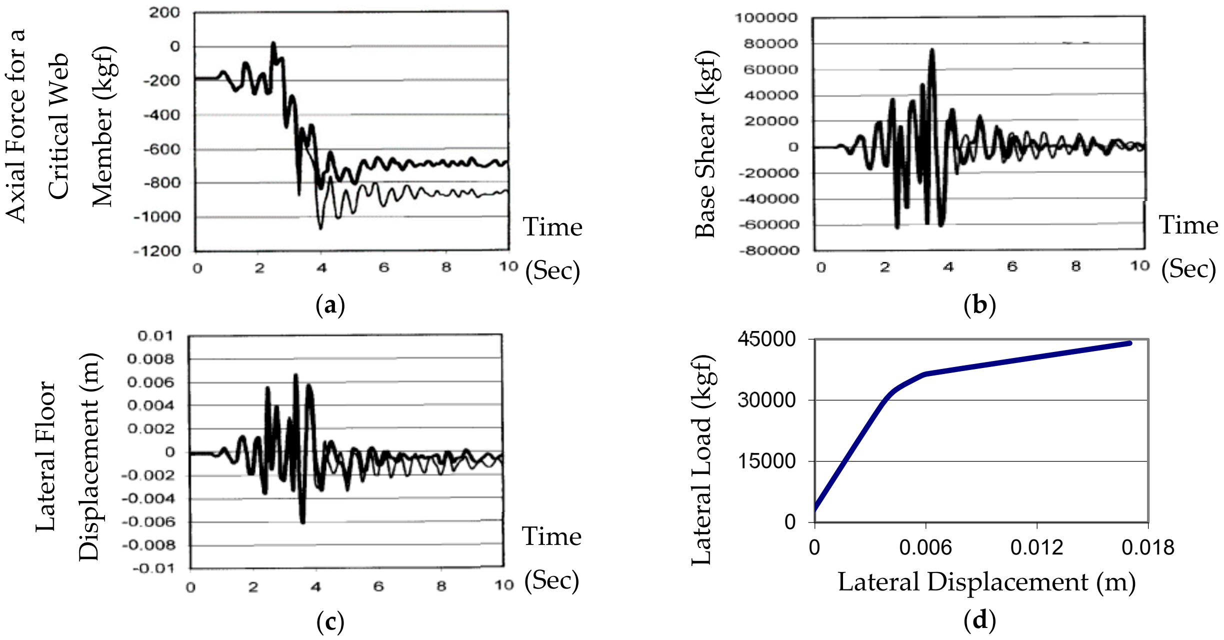
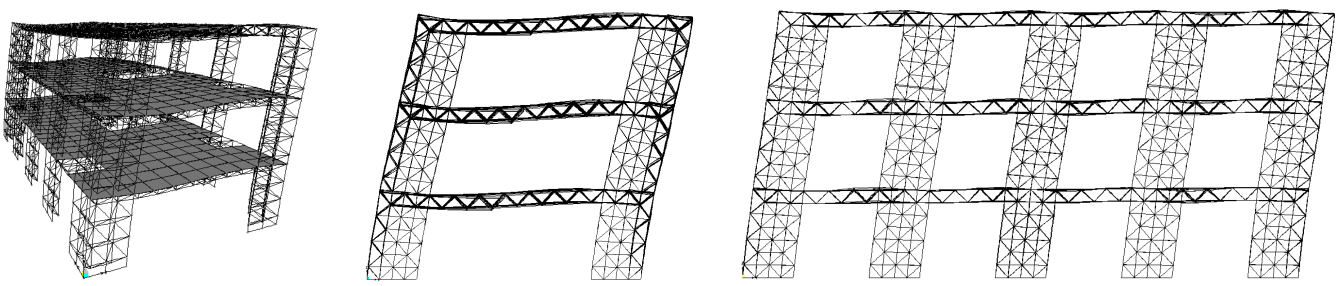


Figure 3. Results of nonlinear analyses: (**a**–**c**) time-history analysis results considering Altadena ground motion with magnified PGA of 1.0 g; (**d**) pushover analysis results.

A spatial braced frame with "X" bracings was also designed with the same positions of columns. Longitudinal bracings were positioned along the perimeter walls, but transverse bracings were located within the plan area to avoid obstructing the entrance. The common design practice based on Iranian Codes (MPORG 2009 and NBR 2008) was followed. In the case of the space grid system, the structural weight (and hence steel consumption) was found to be about half (50%) of the moment frame and 60% of the braced frame sample structures. Figure 4a–c show the dominant first mode of vibration in the space grid building in 3D, x direction, and y direction, respectively. The first and second modes contributed significantly in the horizontal x and y directions, but the seventh mode, dominant in the vertical z direction, only contributed as much as 35%. To ensure at least 90% of the equivalent mass contribution, up to 100 modes had to be considered in a response spectrum analysis.



(**a**) (**b**) (**c**)

Figure 4. Selected results of the first mode of free vibration of the three-storey building: (**a**) 3D response; (**b**) x direction; (**c**) y direction.

2.1.4. Regular Building with Composite Double-Layer Grid Floor

In another study, a rather regular building was considered. The building was composed of composite 1×1 m^2 square on square double-layer grid floors, which is well suited for mass production, in composite action with a rather thin reinforced concrete two-way slab. The building plan was a square of 27 m in dimension and included a 7×7 m^2 central core usually used to accommodate lifts and their surrounding stairways. All the double-layer grids were 50 cm in depth, and the gross storey height was taken as 3.5 m. As far as the gravitational and lateral load-bearing structural system was concerned, three different configurations were employed for the purpose of comparison with each other and with the widely used traditional dual system of concentrically braced and moment frames considered here as a benchmark. The three configurations chosen were as follows:

1. The lateral load-bearing elements were concentrated around the position of the central core;
2. The lateral load-bearing elements were placed at the four corners of the building in the form of four corner angles, in the plan view;
3. The lateral load-bearing elements were considered a combination of (1) and (2) above.

Preliminary investigations shown in Figure 5 revealed that type (3), which consisted of lateral load-bearing elements at both the core and the four corners, was more efficient in terms of structural weight, stiffness, and force distribution.

Figure 5c shows the square-on-square double-layer space grid structure for a typical floor. Topping concrete is not shown for clarity. Figure 5a,d show the plan and perspective views of the space grid structure type (3) mentioned above, respectively. The plan and perspective views of a traditional (or common) type of structure widely used for such buildings (i.e., a dual system composed of moment frames combined with concentric bracings with an analogous form) are shown in Figure 5b,e. A composite castellated beam-and-slab system was used as the floor structure. It should be noted that the thickness of the concrete topping was higher in this system due to the one-way action of the concrete top slab, while in the case of the double-layer composite flooring, the slab acts as a two-way system. Another matter of utmost significance is the use of intermediate columns in the braced frame system, which limits the architectural freedom that can easily be granted with the use of a double-layer grid system covering large spans without internal columns. This is an immense advantage, particularly in parking areas and in structures where relatively large spans are needed without intermediate columns. The floor systems were of the types presented in Figure 5a–c. The designed configurations were modelled using Formian-k software [24,25], which is a versatile tool for generating topological and geometrical models of spatial structural configurations and finite element meshes.

In the analysis model of the spatial grid construction, truss elements were used to represent spatial grid members and thin shell–plate elements to stand for the reinforced concrete topping. The design of the sample buildings was carried out to meet the requirements described in [20,22]. Figure 5f shows the first mode shape of the space grid structure resulting from the generalized eigenvalue analysis of the structural stiffness and mass matrices. Figure 5g shows the contour of dead load vertical displacement for a typical composite double-layer grid floor. Quantitatively, the weights of the designed sample structures are given in the 3D bar chart of Figure 5h. As is observed, the weight of type (3) space grid structure is the least of all the other systems investigated here, and in all cases, the space grid system is considerably lighter than the analogous conventional braced moment frame system. It is interesting to note that, in the analyzed spatial grid systems, the weight of the structure reduces from type (1) to type (3) lateral load-bearing system configurations, while this is not the case in the braced moment frame structures for which even a slight increase in weight is detected in the type (3) configuration compared with others. In brief, the structural weight of the type (3) configuration (both the weight of steel shown in the figure and the weight of the concrete slab) is about half that of the corresponding braced moment frame. Technically, the space grid system is a safer structure due to its considerably better behaviour against progressive collapse. Further studies focusing on the nonlinear static (pushover) and dynamic behaviour and the seismic response of the proposed double-layer spatial structural system for buildings have already been reported in [26]. An investigation has revealed the potentialities of increasing the system ductility (and hence, the seismic behaviour factor) by utilizing the joint flexibility [17] and energy dissipation capabilities introduced in the joints of the lateral load-bearing double-layer walls [27]. Qualitatively, the omission of intermediate columns provides an unmeasurable advantage for architectural designers. Environmentally, using the proposed system instead of the common framed and braced frame steel structures results in much less damage to the environment through the exploitation of steel and raw materials for cement and concrete and, at the same time, leads to a greater reduction in the energy consumed to produce a significant amount of additional steel, cement, and aggregates. Reduced energy consumption apparently helps in reducing the related pollution.

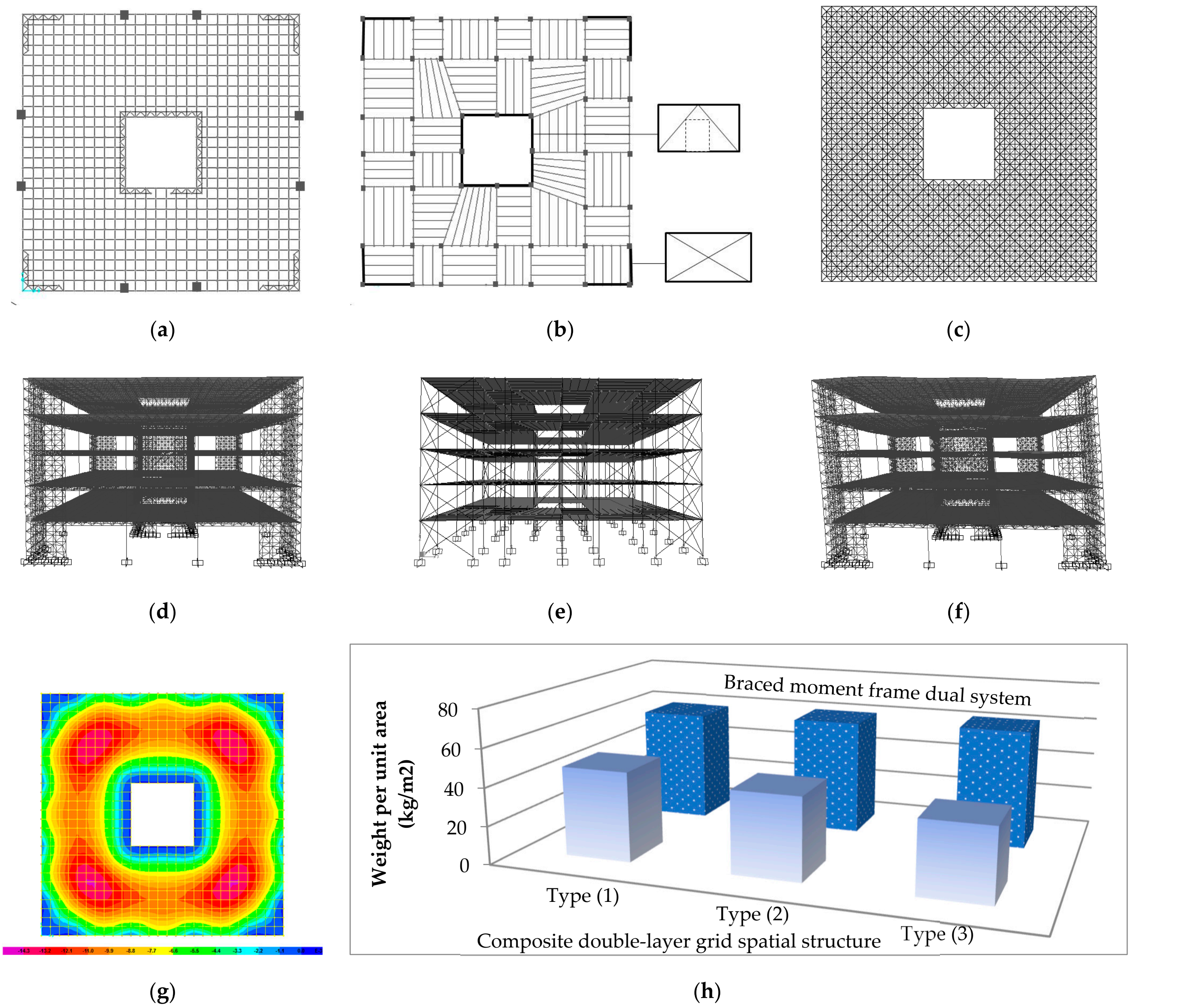


Figure 5. Results of composite double-layer grid spatial floor buildings: double-layer grid of type (3) (**a**) plan view and (**d**) perspective view; (**c**) double-layer square of square grid; moment frame combined with concentric bracing (**b**) plane view and (**e**) perspective view; (**f**) deformed shape of the double-layer grid structure in persepctive; and (**g**) vertical displacement contour for proposed double-layer grid floor; (**h**) comparison of weight per unit area of the three types of double-layer grid compared with braced moment frames.

2.1.5. General Construction and Functionality Considerations

Other than some of the important considerations provided in Section 2.1.3, additional practical considerations in the construction of the proposed building system in terms of architectural design, mass production economics, inspection and safety, and sustainability are discussed below.

- Architectural design: Consider the two types of structures compared above, namely, one with space grid floorings with some partial double-layer grid walls, only in a few panels, and the other, a dual system of braced and moment frames with internal columns. A space grid structure with no internal columns clearly provides the designer with significant flexibility in their architectural design, particularly in parking areas, conference rooms, and interior partitioning and design. Passages for electrical, piping, and ventilation unitscan be accommodated without concerns about clashes with structural members, such as beams and columns, thus enhancing functionality. In terms of the absolute available plan area, the commonly used framed buildings usually contain 250–300 mm thick perimeter walls. Here, the proposed system with partial double-layer grid walls provides nearly the same net plan area as the moment frame system with internal columns and a slightly larger net available area than the braced frame model discussed above. However, the framed and braced frame samples studied here are truly far behind the proposed system in terms of functionality due to their span limitation, which makes the existence of intermediate columns unavoidable.
- Mass production economics: Such systems are most effective when mass-produced within well-organized and lean industrialized production lines, followed by effective on-site management. This requires an initial investment for the construction of the manufacturing plant. Hence, the cost of a building constructed using this system must include costs pertaining to (i) the initial investment of the facility; (ii) construction and operations costs, such as materials, manufacturing, transportation, and erection; and (iii) serviceability, maintenance, and possible demolition and recycling. Investigations must also be carried out to calculate the man-hour per metre of apartment buildings of the type discussed here in different parts of the world. A factory mainly designed for the housing industry should be designed for predefined service life and production capacity. Particularly, in locations at risk of earthquakes with a shortage of skilled labour (e.g., for welding), a number of space grid manufacturing plants may be designed and constructed (based on the demand) to undertake the mass production and mass customization of fast, safe, economic, functional, reliable, and aesthetically pleasing houses, schools, hospitals, administrative, and other buildings to meet the ever-increasing demand of modern societies with the long-term satisfaction of the customer (i.e., a human-centric approach) in mind.
- Inspection, health monitoring, and safety: Every part of the main structure can be easily accessible for inspection and maintenance. The space between the double-layer grids can be used for the passage of piping and future inspection and maintenance, as described for the decking system. As such, due to the existence of adequate space between elements, the system is a viable candidate for intelligent and/or smart structural systems. This allows for the utilization of modern internet-of-things (IoT) [28] sensors to provide real-time information, as well as for the generation of effective digital twins [29–31]. Fire resistance is an issue of concern; however, the tests conducted by Du Chateau [32] on large-span double-layer roof structures revealed good fire resistance. In fact, due to the pronounced resistance of highly indeterminate and redundant space structural systems, local failure can rarely lead to progressive collapse, and the structure is usually capable of providing an alternative load path to withstand fire for a relatively considerable time. Desirable seismic performance as a result of their lightweight and redundancy has been achieved and demonstrated in [26,27]. Finally, a variety of factors related to soil–structure interaction need to be further clarified. Advanced research must be conducted aiming to achieve resilient structures through the desirable proportion-

ing of strength, stiffness, ductility, damping, and energy dissipation capability of such structures in the framework of performance-based design.

- Sustainability: Using the proposed system, all the mentioned versatilities were achieved using less than half of the structural materials used to construct moment frame or braced moment frame systems, which also require the use of obstructing and impeding internal columns. This reduction in weight reduces both the embodied energy and embodied carbon for construction, which will be even further noticeable in mass production and customization settings. Due to the flexibility in design, particularly in adding openings and windows around the structure with minimal obstructing structural members (such as load-bearing walls, columns, and beams), any space can be designed with natural lighting as desired. This in turn increases the average daylight factor (ADF) [33] considerably, supporting low-energy and passive housing, particularly in mass production settings. The structure can be designed to be dismountable for reuse or recycling.

2.2. *Offshore Structures*

For several decades, offshore structures have been designed and built with the use of welded tubular members. Valuable experiences have been gained during the design, installation, and operation of such platforms. As with many other engineering evolutions, alongside admirable achievements, some drawbacks still persist as a consequence of the intrinsic nature of welded tubular structures under the action of variable amplitude fatigue loading caused by influential forces; this is a problem that has resulted in the need for the costly continuous permanent monitoring and inspection of the underwater structure joints. All the developed defects may not be timely recognized. The fatigue monitoring gauges developed by the Fatigue Monitoring Bureau at UMIST significantly helped in monitoring critical points and hot spots remotely at positions where the gauges were installed (Fatigue Monitoring Bureau, 1989 onwards, data commercially in confidence). Hence, the location and installation of such gauges should be such that no critical point is missed. Obviously, the tubular structures currently employed for the construction of offshore platforms, similar to every other structure, behave three-dimensionally in nature and act as braced space frames. However, a clear distinction should be made here between those structures referred to as skeletal space trusses and common tubular structures. At this stage, we concentrate on the jacket type of platforms for use on rather shallow seabed. In recent decades, the behaviour of such tubular jackets has been an active area of research [18].

Thanks to the intrinsic advantages of space grid structures, such as excellent performance in preventing progressive collapse, authors have been investigating the potential use of double-layer skeletal spatial structures with suitable connections for offshore platforms. Research can be equally extended to offshore platforms for wind turbines, which necessitate the use of this type of renewable energy technology [18].

2.2.1. Preliminary Studies: Offshore Double-Layer Spatial Grid Jacket

The initial step is to carry out an initial overall feasibility study of such proposed alternative structures from the conceptual design point of view as well as fabrication and erection, and hence, here, the emphasis is on the overall system behaviour. Accordingly, rather simple configurations were studied. Figure 6a shows a simplified double-layer grid to represent a deck with such a structure. In Figure 6b, a typical jacket-type structure, formed as an assembly of typical modules of the constituent double-layer grids, is shown. For this jacket-type structure on a shallow seabed, the foundation could be built with the use of steel piles, precast concrete caissons at corners, a strip foundation with reinforcement at corners, and so on. The variables considered in the initial parametric studies were the widths at the top and bottom, the height, the thickness (the distance between two grid layers), and the density (the number of subdivisions).

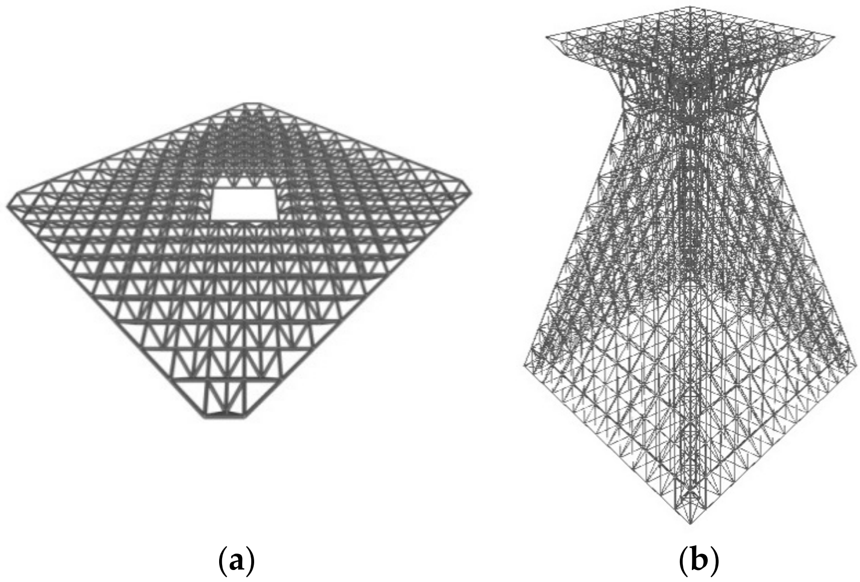


Figure 6. Modular double-layer spatial grid offshore structure: (**a**) deck; (**b**) jacket-type structure.

An existing offshore platform in the Persian Gulf was used together with its design documents, including technical specifications, to act as an acceptable benchmark with the following data: water depth (normal operational condition): 47.2 to 49.2 m; water depth in extreme tidal condition: 47.2 to 50.1 m. Furthermore, the effects of buoyancy were studied in two extreme cases:

1. Sealed members and solid nodes;
2. Submerged condition.

The results of an automated design and redesign loop based on normal engineering calculations/assessment revealed that the proposed space truss jacket had 25% less weight than the benchmark existing project. Furthermore, a considerable amount of steel material could be saved by using double- and triple-layer grids in place of traditional flooring to save the material consumption of the deck by 50% compared with the traditional one. At the same time, the displacement of the space grid jacket was considerably reduced under the designed current and wind loading, indicating higher rigidity of the spatial grid platform.

2.2.2. Real-World Case Study: An Off-Shore Platform in the Persian Gulf

In a more refined study, another existing offshore platform constructed in the Persian Gulf in 1991 was employed as the benchmark structure. The platform is mainly constructed to accommodate the technical personnel together with some heavy equipment. It was installed on a seabed at a depth of 60 m. The jacket is symmetric and regular. The decks are supported on four batter piers/piles at the four corners with a slope of 1 to 10. The width of the jacket at the top working point is 12.2 m. The platform has a boat landing, two bumpers, 24-inch fire pipelines, and other common facilities and equipment. Some noteworthy geometrical characteristics are given in Table 2.

According to the design documents, the weight of the structures of the decks and the deck to pier structure is 215 tons and the weight of the jacket piers/piles above the seabed is 426 tons. The sum of the design live loads on all the decks are 752 tons and the total weight of flooring corrugated plates, railings, etc. are 117 tons. Other related weights such as the weights of boat landing and bumpers have also been considered.

Utilizing Formian [24,25], four different structural configurations were generated with different geometrical forms, densities, etc. A consistent approach was adopted to ensure the reliability of the designs to enable a meaningful comparison. The API Design Criteria and Procedures [34,35] were followed, considering load cases, as well as loading conditions and combinations, and available regional data and design guidelines were considered, including dead loads, live loads, environmental loads, construction loads, static and dynamic wave loads, accounting for marine growth thickness and roughness, wind loads, current, hydrodynamic and earthquake loads, fabrication, handling, launching and installation forces, etc.

Table 2. Noteworthy levels with respect to the mean free sea water level from topographic wetness index (TWI) in the Persian Gulf.

Working point:	(+) 6.50 m
Pile connecting to Leg:	(+) 4.93 m
Level 1: horizontal bracing	(+) 4.00 m
Level 2: horizontal bracing	(−) 11.00 m
Level 3: horizontal bracing	(−) 27.00 m
Level 4: horizontal bracing	(−) 44.00 m
Mud mat	(−) 60.00 m
Cellar deck:	(+) 10.10 m
Lower deck:	(+) 14.80 m
Upper deck:	(+) 18.60 m
Roof deck:	(+) 22.40 m
Helideck:	(+) 25.40 m

For the purpose of all static and dynamic analyses, SAP 2000 (Version 14) [36] was used, together with its steel design module. The requirements of the API [34,35], AISC [22], and Code of Practice for the Design of Space Structures [20] were simultaneously met. The seismic analysis included pushover, response spectrum, and time-history analyses based on the results of seismic risk analysis carried out for the region (i.e., recommended peak ground acceleration and design response spectrum). The time history analyses were carried out under excitation of seven different recorded actual earthquake time histories that had taken place around the region (PEER data base [37]) from which the average response values were used in design.

Figure 7 shows the preferred configuration for the platform under consideration resulting from the above comparative investigation. Several free-vibration mode shapes with significant modal participation are shown in Figure 7.

The results reveal that the maximum lateral displacement of the designed double-layer grid spatial offshore structure, composed of jackets and superstructures undergoes lateral displacements at its top deck levels very close to those corresponding to the existing tubular benchmark offshore structure under the action of wind, wave, current and earthquake loads, demonstrating that the spatial grid structure has been so designed to have rather identical rigidity (stiffness) with the existing benchmark platform; however, the weight of steel material used in the spatial grid system is considerably less than its traditional counterpart, as demonstrated in Table 3 below.

Table 3. Weights of jackets, superstructure, and total structural weights (in tonnes) of the proposed spatial grid in comparison with the existing tubular offshore structure along with the percentage of material saved by using the proposed system.

Type	Existing Benchmark Tubular Platform	Double Layer Grid Spatial Offshore Structure	Percentage Reduction
Weight of the jacket (substructure)	426	249	41.5%
Weight of the superstructure (decks)	215	45	79.1%
Total weight of jacket and superstructure	641	294	54.1%

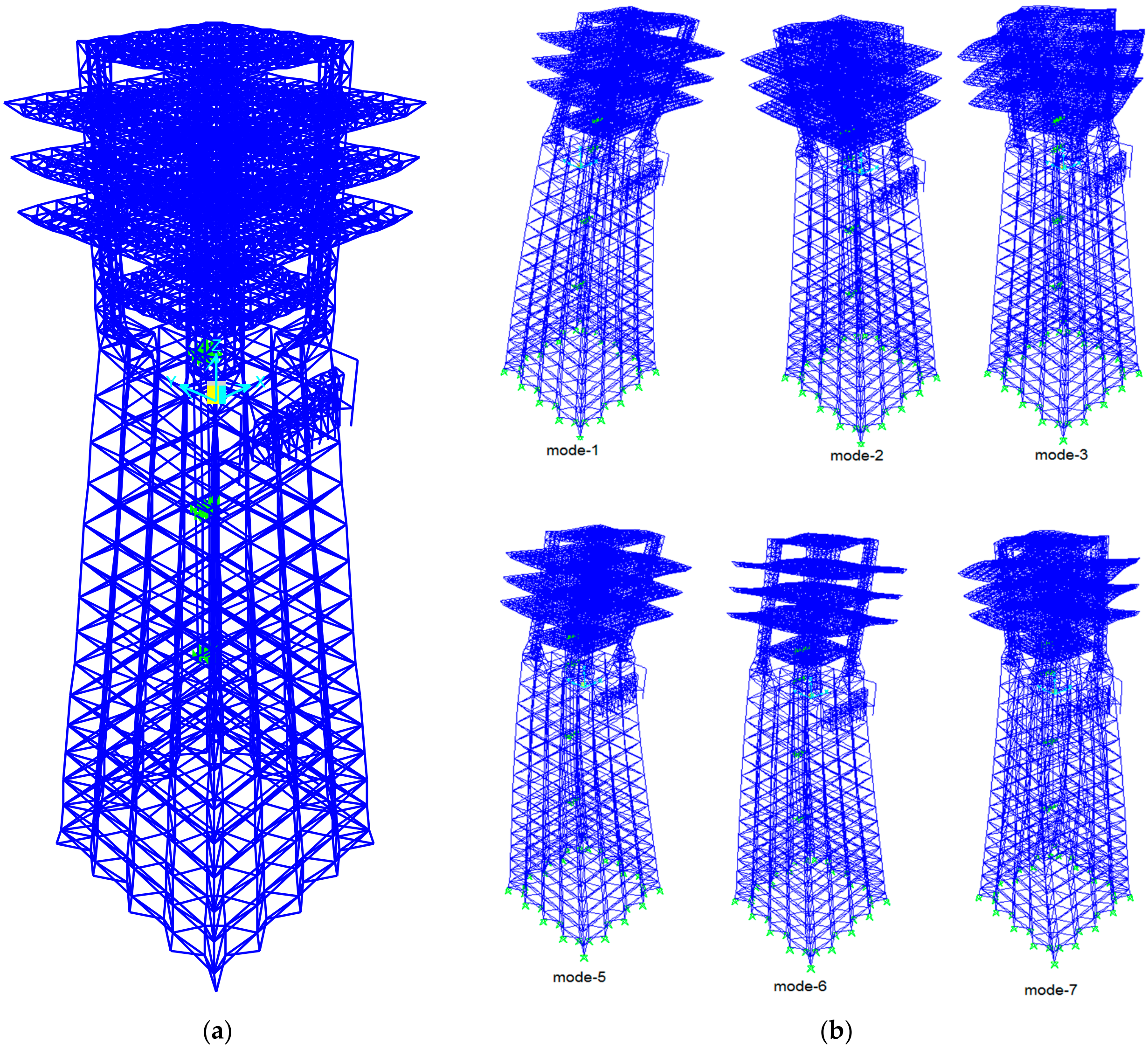


Figure 7. (**a**) Preferred spatial structure configuration for the offshore tower; (**b**) six sample vibration modes for the preferred spatial offshore tower.

2.2.3. General Construction and Functionality Considerations

The general findings derived from experimental results, along with the consideration of further avenues for the exploration of spatial grid jacket offshore systems, suggest less material consumption; lighter weight; lighter handling equipment; ease of fabrication and erection; less damage to the environment; the possibility of industrialized production and prefabrication, resulting in less time and lower cost; a higher quality management standard, controllable stiffness, and ductility in accordance with the desired performance; and higher level of reliability. Additional important considerations in terms of fatigue, future research paths, and sustainability are discussed below.

- Fatigue: Given that displacement is reduced by a factor of eight compared with the traditional tubular structure, this may suggest improvement in the fatigue behaviour of the parts of the system that undergo variable amplitude loads under displacement control. If one achieves a considerably longer fatigue life of a suitable type of well-detailed friction grip-bolted connections for such space structures, the old problem of the fatigue fracture of welded tubular joints may also be resolved. Furthermore, due to high redundancies, these space structures are not as vulnerable to local fatigue failure as tubular structures.

- Future research paths: An area of concern is related to the amount of pressure induced by stream flow and wave on rather dense skeletal space structures both on the front face and on the leeward side. Another important domain of investigation is the seismic effects of this structure with considerably higher rigidity in the context of soil–structure interaction for different soil conditions. Further studies are needed on the dynamic and seismic behaviour; detailed specifications for design, fabrication, and erection; features related to construction management; more sophisticated forms; lifting analysis; and the feasibility of use with required modifications for deeper platforms. Furthermore, the fatigue behaviour of joints, especially under low temperatures, and the effects of corrosion fatigue should also be explored. Finally, various aspects pertaining to the continuous health monitoring of the structure must be investigated. This includes a thorough investigation of the impact of water pressure, waves, etc., on automatic visual assessment techniques [38], using subsea LiDAR instruments [39], along with other smart underwater IoT (IoUT) instruments [40,41].
- Sustainability: One clear benefit of employing this system is the considerable reduction in the weight of construction materials, which will directly reduce the embodied energy and carbon of the project. Due to the bolted joints, instead of the welded tubular members, this system can also be easily deconstructed for reuse/repurposing, or recycling, contributing to the circular economy. The higher possible fatigue life increases the service life of the structure and enhances sustainability. Finally, the eight-fold reduction in displacement of the structure under dynamic loading suggests that this type of system can work well with wind turbines for offshore renewable energy production. This includes the possibility of using gridded spatial structure jacket systems for the foundation (base) of offshore wind turbines in transitional water depths (e.g., around 25–50 m) [42,43] as an alternative for the current tubular jacket systems (e.g., Beatrice offshore wind farm off the coast of Scotland). Three sample designs for the base of wind towers using offshore spatial structures are provided in Figure 8.

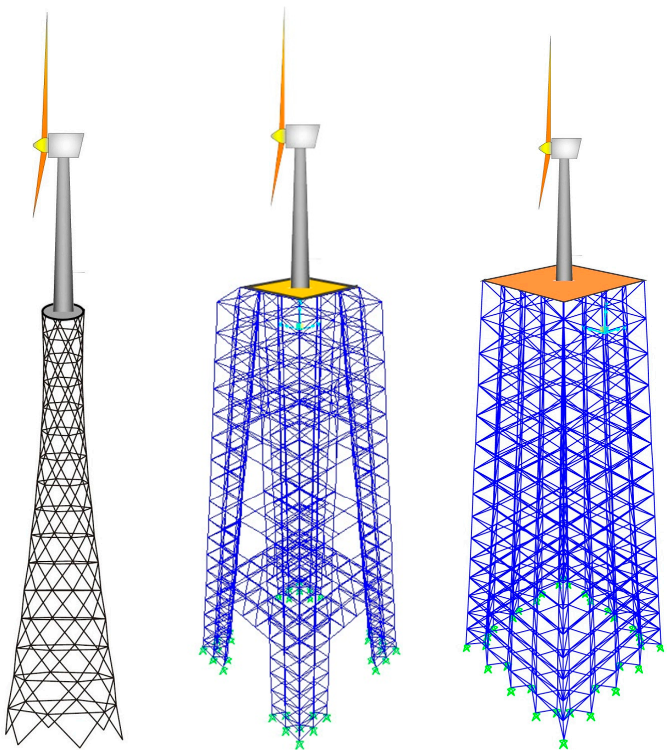


Figure 8. Three example design options for the base of offshore wind turbines inspired by offshore spatial grids.

2.3. Reconstruction and Preservation of Heritage Buildings

Consider the topic of the rehabilitation and reconstruction of aging and ancient cities with geometrically custom, free-form, or smooth components (e.g., hemispherical domes). One such example is provided in Figure 9, where medieval urban dome-shaped developments of this type are prevalent, especially in the central Iranian desert (Kavir). Such old cities still have a considerable number of residents and, in many cases, must be further preserved due to their cultural and historical significance (e.g., supported by the UNESCO World Heritage Centre [44]). Given the established ability of spatial structure grids to foster the creation of custom free-form geometries (Figure 1a,b), they may be employed for fast and large-scale reconstruction of ancient cities and urban developments [19], particularly after natural disasters.

Figure 9. (**a**) Artistic impression of the domes (Gonbad) in the central Iranian desert (Kavir) of Koum by Madam Jane Dieulafoy; (**b**) digital model superimposed onto the picture.

2.3.1. The Proposed Spatial Structure System for Geometry-Preserving Reconstruction

The process of design and reconstruction of these custom shapes (in the case of Figure 9, hemispheres) using spatial structures requires two main frameworks:

1. Generating the geometric digital twin of existing facilities (Figure 10a);
2. Using this geometry to generate modular spatial structural systems, specifically designed to address the serviceability needs (Figure 10b).

The automatic generation of geometric digital twins using optical metrology (such as laser scanners and photogrammetry) has been extensively investigated in [19]. For instance, in the case of hemispherical domes, one can automatically select two convergent images from a network of overlapping images, taken from these types of hemispherical domes, to reconstruct the domes with millimetre-level accuracy [19]. In other cases, advanced image and point cloud processing methods can be employed (e.g., unsupervised learning strategies) to generate the 3D as-built model, as depicted in Figure 10a. In the case shown in Figure 10a, a photogrammetry-based 3D reconstruction is carried out to generate dense 3D point clouds from images taken using drones. The point cloud was then fed to the robust sphere detection program, as described in [45,46] (Figure 10a; middle), where a final building information model (BIM) could then be generated.

For the latter case, Figure 10b shows the three stages required for the design optimization of the individual objects, which are as follows:

1. Spatial structure discretization of model: During this stage, each BIM element was decomposed into a set of spatial structures with single, double, triple, etc., layers. For instance, the case shown on the left side of Figure 10b shows a Formex representation [24,25] of one possible type of single-layer space grid discretization solution. It is possible to automate this part using visual geometric programming from the generated BIM.
2. The design of standard inputs: In this step, the necessary load combinations, as well as the method of design (e.g., load resistance factored design (LRFD) [22,47]), were considered for establishing the design optimization strategy. Depending on the region

and municipality, different standards exist, such as the ASCE [48] for the US, the DIN for Germany, and the National Building Code (NBC) for Canada. For instance, the example shown in the middle part of Figure 10b demonstrates the loads as a result of live, dead, wind, and snow loads, acting upon a hemispherical dome using the Canadian NBC.

3. Design optimization for sustainability: Finally, the aforementioned steps were utilized as input in an iterative (and in many cases, heuristic) optimization process to find the best combination to minimize the weight of the structure. This optimization process for weight directly minimizes both embodied energy and carbon. Other design and sustainability considerations, such as ADF [33], cost, etc., may be added to form a multiobjective optimization problem [49]. These optimization problems can be solved using heuristic methods, such as artificial intelligence (AI) optimization using genetic algorithms, to find the Pareto optimality [50]. In the example shown on the right of Figure 10b, the optimal shape and size of each element of a one-way Schwedler dome for weight minimization was determined using a genetic algorithm framework.

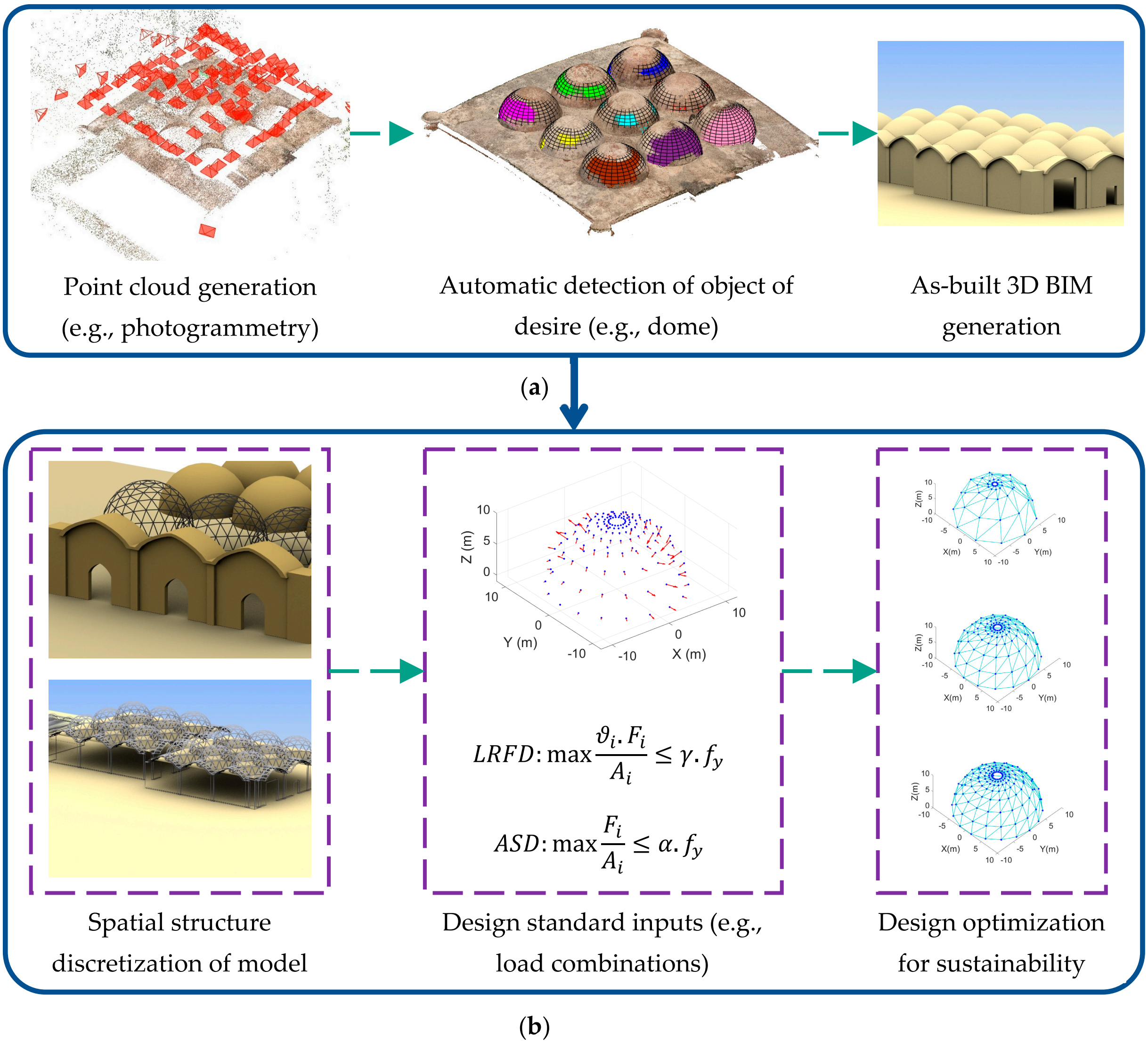
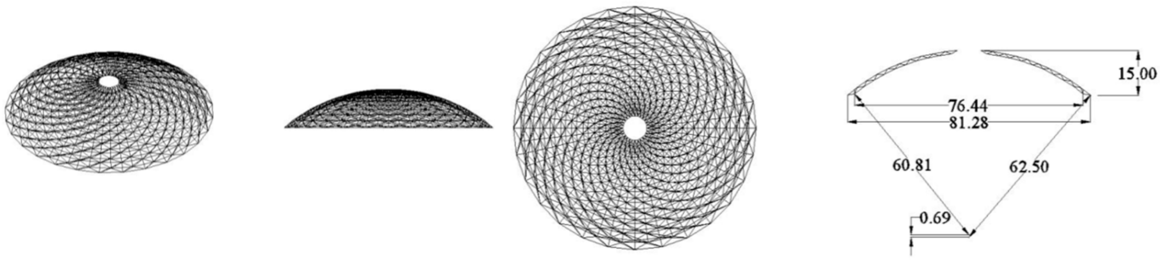


Figure 10. Proposed spatial structure design optimization for geometry-preserving reconstruction considering sustainability: (**a**) automatic generation of a 3D BIM model using point clouds generated from optical instruments (e.g., laser scanners or drones); (**b**) design optimization for individual BIM components to minimize weight, embodied energy, and embodied carbon.

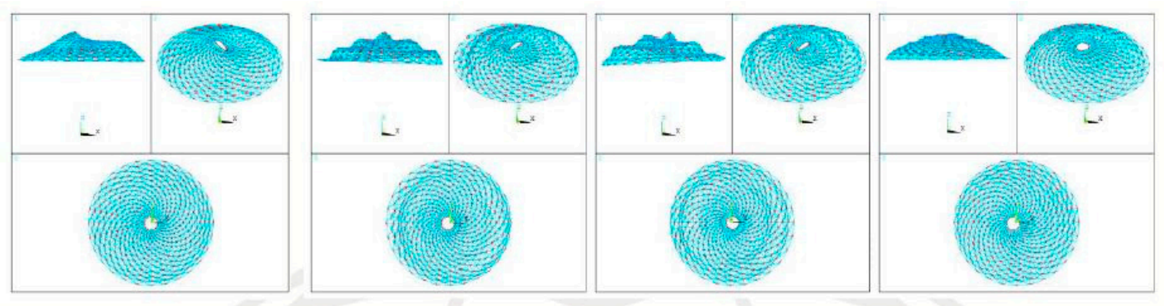
2.3.2. The Spatial Structure Reconstruction of Domes: Seismic Response Analysis

Comprehensive research studies on the seismic behaviour of spatial dome structures have revealed excellent potentialities of braced dome spatial structures to withstand severe earthquakes if properly designed and constructed to meet the requirements of the Iranian Code of Practice for Spatial Structures [20].

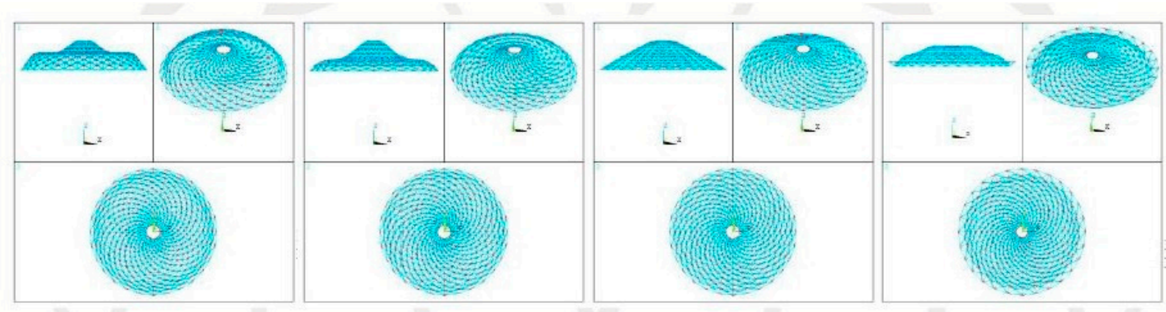
Figure 11a shows a sample double-layer lamella dome structure. Several mode shapes corresponding to larger modal participation in horizontal and vertical directions are shown in Figure 11b,c, respectively. In the modal analysis of these space domes, numerous modes of vibration contribute to the dynamic response of the structure and need to be considered when performing a modal analysis.



(**a**)



(**b**)



(**c**)

Figure 11. (**a**) Lamella double-layered dome specifications; and modal shapes corresponding to the four vibration modes with larger modal participation in (**b**) horizontal direction (Modes No. 6, 88, 77, and 207 in the order of modal contribution) and (**c**) vertical direction (Modes No. 21, 10, 5, and 51 in the order of modal contribution).

In addition to the response spectrum analysis, an extensive number of linear and nonlinear time-history analyses were carried out to investigate the influences of a variety of important parameters on the seismic response of the dome structures under consideration. The parametric studies included an investigation of the effects of material properties, member slenderness ratios, member imperfections, joint flexibility, rise-to-span ratios, damping ratios, and density (size of modules). The nonlinear analyses included nonlinear material behaviour as well as geometrical nonlinearity. Possible modes of instability such as member buckling, nodal instability (including nodal torsional instability), coupled member and node buckling, local group instability, snap-through buckling, instability around circumferential parallels, line instability along a part of a meridional line, and general overall instability were analyzed. Furthermore, the accuracy levels achieved through different nonlinear dynamic analysis procedures were compared. In this study, two analysis programs were used: early versions of NISA [51] and ANSYS [52]. Eleven recorded time histories of ground motion were used in two cases: (i) a single horizontal component, and (ii) three translational components of ground motion in orthogonal directions acting together.

2.3.3. The Spatial Structure Reconstruction of Domes: Nonlinear Dynamic Response

This section provides the results of the time-history nonlinear analysis of the proposed dome structure. In this sample analysis, members were modelled to account for member buckling. An initial imperfection (maximum initial lateral deflection or out of straightness of a member) equal to 1/500th of the member length was assumed for each truss member. In such domes, the common practice is to emphasize their nonlinear geometric behaviour; however, Refs. [15,53] revealed the importance of nonlinear material behaviour as essential as geometric nonlinearity, which should be considered simultaneously with local and overall buckling on the static and dynamic response of these domes, to achieve a realistic prediction of their response. Hence, here, both geometric and material nonlinearities were included in the analysis. The distributed mass was defined for structural members, while the masses corresponding to claddings, mechanical and electrical facilities, and snow loads were assumed to be lumped at structural nodes appropriately.

The nonlinear dynamic analysis of the dome also included single- and triple-component excitations. El Centro ground motion was applied and scaled with different scale factors; PGA values were scaled to 0.10 g, 0.25 g, 0.35 g 0.50 g, and 0.75 g. Some representative results are provided in Figure 12.

Figure 12a corresponds to the time history of the dynamic response of a member located at the uppermost outer-layer ring when the PGA was scaled to 0.35 g and demonstrates the large discrepancies between the analysis results with the application of three- and the single-component excitations on the unsafe side. When the same form of acceleration time history is scaled to 0.75 g, a shift in the mean value of the response of the member can be observed in both diagrams, which is attributed to the single- and triple-component excitations (Figure 12b). However, in the case of three-component excitation, a sudden unloading of the member occurred, which is indicative of member buckling. By contrast, under single-component excitation, a sudden decrease in resistance to a residual strength (post-buckling strength) can be observed. Although this phenomenon occurred for a limited number of members under the PGA of 0.75 g, it did not lead to overall instability. It was found that the high degree of indeterminacy of the structure led to the redistribution of the load path and provided satisfactory resistance against progressive collapse. Reducing the slenderness ratios for those few members that acted as Member No. 64 prevented such a shift in the mean value of vibrating stress, and the structure behaved safely under the maximum PGA of the exciting earthquake scaled up to gravitational acceleration.

The nonlinear vs. linear response showed a reasonably acceptable ratio of the maximum linear to maximum nonlinear response, and controllable ductility was achieved by selecting appropriate slenderness ratios for different members just sufficient to prevent buckling under the action of the expected earthquake, and its corresponding expected behaviour was considered based on a performance-based design. The ratio of linear–nonlinear response increased as the PGA increased, and the nonlinearity of behaviour extended.

Due to the particular features of the sample dome, even with the maximum PGA applied, the seismic effects did not cause overall failure. The differences between the results of single- and three-component excitations were found to be numerically considerable. As far as the dynamic behaviour is concerned, different responses were observed, particularly with increasing PGA and the dominance of the nonlinear response. It can be seen from Figure 12c,d that, under a PGA of 0.75 g, at the onset of overall nonlinear behaviour, sudden unloading occurs in some members for which the oscillation takes place above and below a shifted mean value of stress. The analysis of the single-component excitation did not allow us to assess this effect thoroughly, since the contributions of the other two components (in particular, the vertical component) were not taken into account. The effect of three-component excitation became more pronounced in the nonlinear analysis and as the acceleration scale factor increased from 0.35 g to 0.75 g. The percentage differences between the stresses calculated from the nonlinear analysis were less than those resulting from the linear analysis, due to the redistribution of forces within the highly indeterminate structure in the nonlinear range of behaviour. The differences between the results of single- and triple-component excitations became more significant as the ratio of span-to-crown height increased, and the effects of the vertical component became more prominent for shallower domes. Conversely, as this ratio decreased, the influence of horizontal components became more pronounced. As braced domes exhibit dominant three-dimensional behaviour and usually have considerable span dimensions, it is expected that a three-component excitation be a natural choice for the study of the seismic response of such structures. With the ever-increasing advances in computational facilities, it is reasonable to include three-component excitations in the design practice, which can lead to more realistic results with no significant additional computational efforts/costs. The error in disregarding the transverse and vertical components for the dome analysed here was to the extent that it did not justify the use of single horizontal component excitation for the study of the seismic behaviour of such a dome. Hence, appropriate recommendations are needed in relevant codes of practice applicable to space structures, particularly considering near-field effects. Such recommendations have already been included in the Iranian Code of Practice for Space Structures [20]. The effects of imperfections were found to be considerable; however, by limiting the initial imperfection of members to an achievable practical value of 1/1000th of the member lengths, such effects can be ignored [16].

In relation to the application of spatial braced dome structures in the reconstruction of seismically damaged heritage buildings, a typical bazaar and a typical mosque [16], both existing in the city of Tabriz, were considered for the demonstration of this notion. These types of buildings were built centuries ago with available materials (i.e., masonry), and although the engineers at the time were aware of the importance of forms such as arches and domes in masonry structures, their efforts would not lead to the construction of buildings capable of resisting severe earthquakes, as observed in the city of Bam in 2003 and many places around the world in recent decades. Figure 13 shows a graphical representation of this type of spatial grid structure composed of a braced dome supported by a double-layer grid roof structure and grid piers at corners. Due to the very high probability that such a masonry building would be damaged under a severe earthquake event, it is desirable to reconstruct the building preserving the form and entity of the building as a historical and cultural heritage. In the case of a large seismic event leading to the vast destruction of these buildings, such as the disastrous complete destruction of the historical heritage site of Arg-e Bam, a remarkable and noteworthy work of art, considered an architectural and engineering landmark and a hallmark in town planning. The use of such space grid structures that can be easily and quickly constructed to preserve the form and identity of damaged buildings while ensuring excellent seismic behaviour to withstand future earthquakes will definitely be a right, practical, and economic solution. The current efforts to reconstruct the Arg by means of traditional heavy masonry materials to regain its identity as much as possible have been slow, impractical, and uneconomical, and a continuous effort to reconstruct some possible parts of the Arg has had little effect since they are again prone to earthquake damage under a possible future earthquake event.

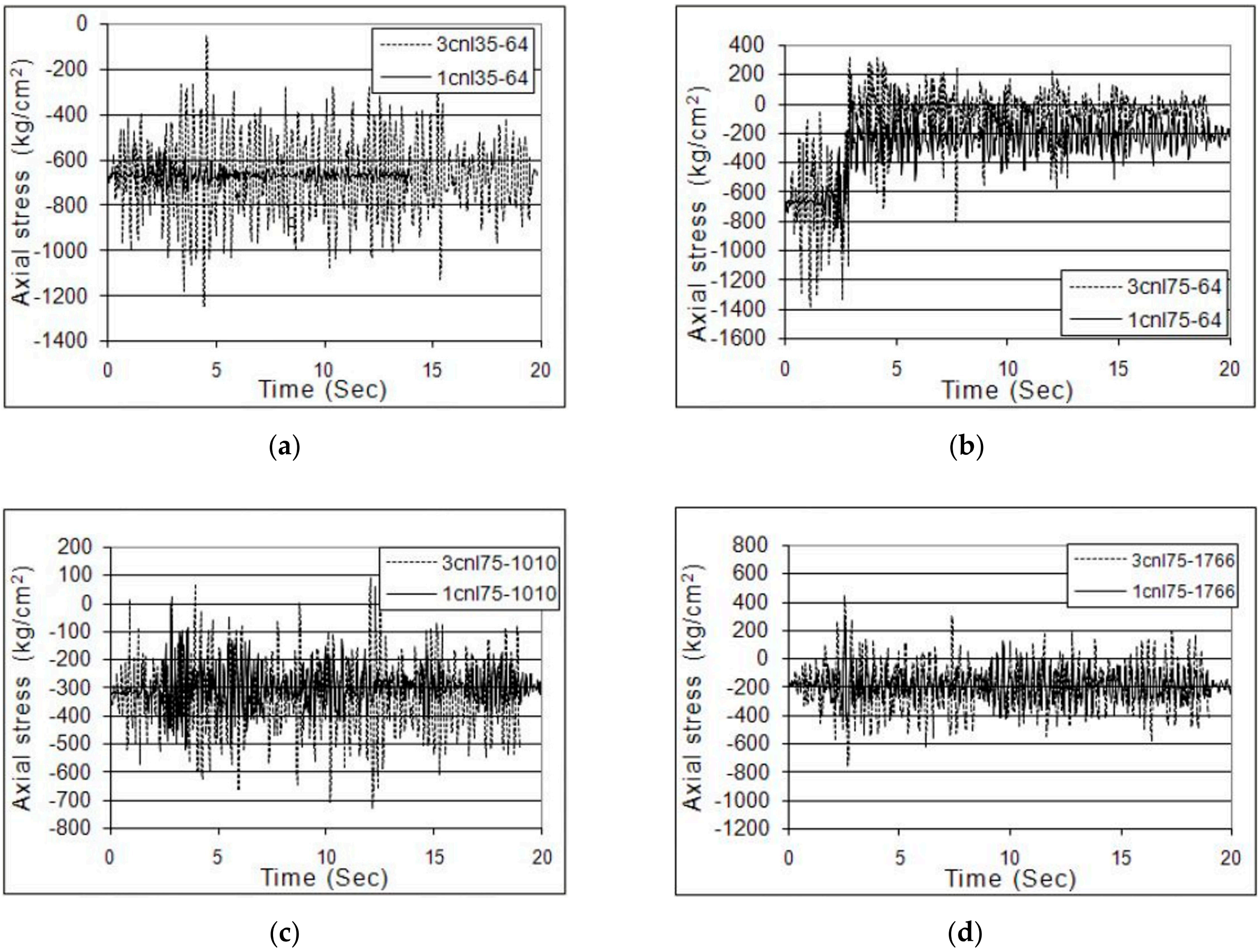


Figure 12. Three-component vs. single-component nonlinear time-history response of average axial stresses for selected members: Member No. 64, located at the uppermost outer-layer ring with PGA (**a**) scaled 0.35 g and (**b**) 0.75 g; (**c**) Member No. 1010, a member of the internal layer at the second circumference from the top; (**d**) Member No. 1766, connecting a support to the adjacent outer-layer node.

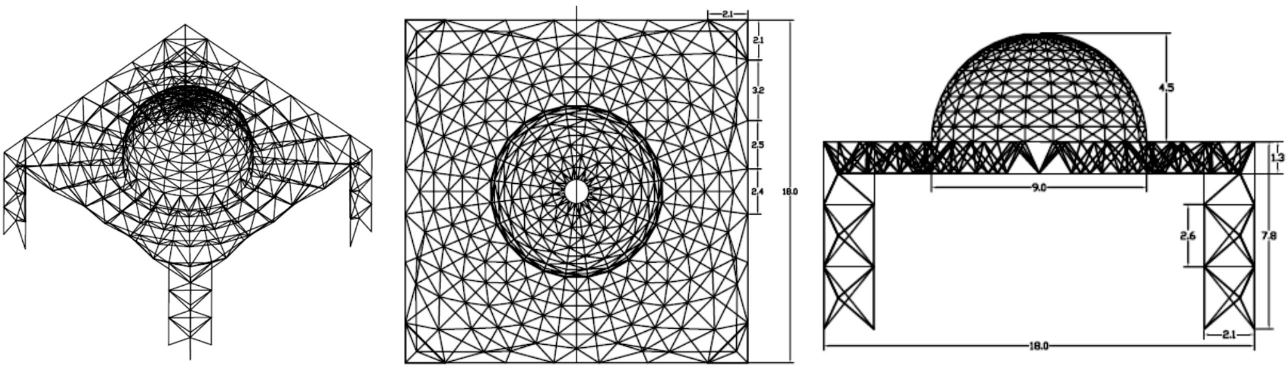


Figure 13. Design of heritage domes reinforced using spatial structures.

A series of response spectrum analyses with a combination of 100% of one component with 35% of the other two components of ground motion acting in three perpendicular directions as well as a considerable number of nonlinear time-history analyses have proven that such structures, if designed according to a reliable code of practice (e.g., [20]) to prevent overall buckling and local failure, will not fail under severe earthquakes up to the maximum considered earthquakes [16]. These structures are safe, reliable, cost-effective, and speedy and preserve the functionality of the original building in harmony with the built environment. Even cladding by means of newly developed lightweight materials can be chosen and installed to provide virtually the same visual form as the original structure before incurring seismic damage. The importance of this topic is not limited to Iran and a few other countries. Most of the earthquake-prone countries in southern Europe have many masonry domes and arches, which may also benefit from the ideas proposed here.

3. Conclusions

The ideas exemplified above can be extended with virtually no limitations. They have also been applied to temporary and permanent transmission towers [54], and by many researchers to shelters; temporary housing for post-disaster situations [55]; deployable, expandable, and demountable systems [56,57]; cooling towers [58]; and many more cases. The joy of experimentation in building creative, free-form structures with unique features will continue to drive further progress as part of the historical challenge of human beings to overcome nature's obstacles and symbolize humans' capabilities at a particular place and time. These are certainly valuable advancements to be encouraged. The authors see no contradiction between these efforts and those presented in this study. However, further efforts are needed from the engineering community to take the most advantage of limited available resources. In this context, the authors hope that the insights drawn from this study clearly highlight the fact that modular skeletal space structures still have many applications and advantages to offer in order to meet the needs of contemporary societies combining economic and environmental aspects to build sustainable and resilient structures with an outlook towards the future.

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