The Journal of the IASS welcomes contributed Technical Papers pertaining to the design, analysis, construction, and other aspects of the technology of all types of shell and spatial structures. In addition, Project Descriptions about realizations of innovative or noteworthy spatial structures are particularly solicited. All Technical Papers and Project Descriptions are open to written discussion, which will be published, possibly together with a response from the author(s). Contributors need not be members of the IASS.

Requirements and instructions for submitting Technical Papers, Project Descriptions and Discussions are presented on the inside of the back cover of each issue and also appear on the IASS website.
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Purpose of the IASS

The continuing development of design, analysis and construction techniques of shell and spatial structures has resulted in an increasing fund of information of practical interest to architects, engineers, and builders. The IASS, founded in 1959 by Eduardo Torroja and a number of other prominent pioneers in the field, has as its goal the achievement of further progress through an interchange of ideas between all those interested in lightweight structural systems such as lattice, tension, membrane, and shell structures. To this end, the IASS organizes annual Symposia and occasional Colloquia, fosters the activities of several technical Working Groups and sponsors the publication of their reports, and publishes this *Journal* four times yearly.

Membership Benefits and Fees

All those interested in any aspect of design, analysis and construction of spatial or shell structures, as well as those interested in the research into their behavior, are welcome as members of the IASS. The benefits of membership include:

- Reduced registration fees at IASS Symposia and Colloquia
- Participation in the Working Groups of the Association
- A copy of newly published reports of every Working Group
- A subscription to this *Journal of the IASS*

The current annual membership fees (in euros) are:

- **Individuals** who share the aims of the IASS: €85
- **Students** at recognized institutions of higher learning: €15
- **Collective**: organizations or firms which share the aims: €425

Currently Active Working Groups

1. Technical Expert Group on Cooling and Solar Updraft Towers
2. Technical Expert Group on Masts & Towers
3. Concrete Shell Roofs
4. Tension & Membrane Structures
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21. Advanced Manufacturing and Materials

Further Information

The Association is governed by its Executive Council, elected by the members. The Council, in turn, elects the officers and appoints chairs of the standing committees and Working Groups.

For additional information about the Association and for membership application forms please visit the IASS website or contact the Secretariat of the IASS (see bottom of previous page).

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INTRODUCTION

The International Association for Shell and Spatial Structures (IASS) symposia are much anticipated events for engineers, architects and researchers. The symposia attract hundreds of participants each year from around the world who come together to exchange latest ideas and exciting developments in the field and to network with professional colleagues. The symposia are also well known for friendly and memorable social activities for accompanying persons. The IASS symposia have been successfully held for over 60 years in various countries such as Brazil, China, Germany, Japan, the Netherlands, Poland, South Korea, Spain, the UK and the USA. The only time the symposia graced the Oceania region was in 1998, in Sydney, Australia.

It is wonderful that the IASS 2023 will be held in Melbourne, the cultural capital of Australia. Apart from art galleries and museums, the city has many innovative structures and fascinating architecture, where splendid Victorian buildings alternate with modern skyscrapers. Melbourne’s multicultural background offers a wide variety of cuisines, a sparkling nightlife and unique tourist attractions.

THEME AND TOPICS

The theme of the IASS 2023 symposium is Integration of Design and Fabrication, which is becoming increasingly important with the developments of digital technologies in both design and manufacturing. The symposium covers all aspects related to material, design, computation, construction, maintenance, history, environmental impact and sustainability of shell and spatial structures in all fields of application. The symposium topics include (but are not limited to): conceptual design; computational form-finding; optimisation; computational methods for analysis; detailing and construction; advanced manufacturing; digital fabrication; shell structures; tension and membrane structures; inflatable structures; framed and lattice structures; gridshells and bending-active structures; tensegrity systems; adaptive systems; deployable and origami systems; advanced and bio-based materials; temporary structures; metal spatial structures; timber structures; glass structures; historical structures; teaching and education.

DATES AND VENUE

The symposium will be held on 10–14 July 2023 at Melbourne Convention and Exhibition Centre.

REGISTRATION AND FULL PAPER SUBMISSION

Registration for attending IASS 2023 is now open and early-bird registration closes on 31 March 2023. Authors with accepted abstracts are invited to submit full papers.

KEY DATES

- Submission of abstracts:                      31 Jan. 2023
- Notification of abstract acceptance:          15 Feb. 2023
- Submission of full papers:                       31 Mar. 2023
- Early-bird registration ends:       31 Mar. 2023
- Notification of full paper acceptance:        early May 2023

SOCIAL PROGRAM

Social events will be organised for participants and accompanying persons, including a welcome reception, a gala dinner, technical visits and other events. Sightseeing tours will be arranged for accompanying persons.

CO-CHAIRS OF ORGANISING COMMITTEE

Prof. Yi Min ‘Mike’ Xie (RMIT University)
Prof. Jane Burry (Swinburne University of Technology)

FURTHER INFORMATION

Email: info@IASS2023.org.au
Website: www.IASS2023.org.au
ANNOUNCEMENT
IASS 2024 SYMPOSIUM
REDEFINING THE ART OF STRUCTURAL DESIGN
26-30 August 2024, Zurich, Switzerland

INTRODUCTION
The International Association for Shell and Spatial Structures (IASS) has focused on advancing design, engineering, materials and methods since its foundation in 1959. It attracts architects, engineers, and practitioners who play crucial roles in the integration of structural engineering and architecture. The Swiss engineer Heinz Isler was an IASS founding member, and Switzerland has a renowned history in this domain and in the association.

The 2024 IASS Symposium will be held at ETH Zurich, situated in the heart of Europe. Established in 1855, ETH Zurich is one of the world’s leading universities in science and technology and is known for its cutting-edge research and innovation.

ETH Zurich’s world-renowned Department of Civil, Environmental and Geomatic Engineering and Department of Architecture both have a long history of structural design excellence. As the Alma Mater for engineers such as Carl Culmann, Othmar Ammann, Robert Maillart, Heinz Isler, Christian Menn, Santiago Calatrava and Joseph Schwartz, ETH Zurich maintains both a historic and a contemporary leading position in structural design research. This position is currently exemplified by an estimable strategic commitment to collaborative research on digital fabrication and industrialised construction with impressive research facilities and its engagement with the National Centre of Competence in Research (NCCR) Digital Fabrication.

THEME AND TOPICS
The main thematic focus of the conference will be the historic and ongoing intersection of technology with informed expression in structural design. The theme of the conference will be Redefining the Art of Structural Design, and will acknowledge the exemplary history of the IASS and new groundbreaking innovations in our field. The symposium aims to further develop the classic characteristics of structural design - Efficiency, Economy and Elegance - and extend them with Environment and Ethics to robustly address the current challenges faced by our discipline and planet.

SYMPOSIUM DATES AND VENUE
The symposium will take place from 26 to 30 August 2024 at ETH Hoenggerberg, in Zurich, Switzerland.

Zurich is the largest city in Switzerland. It has excellent international flight and European train connections, with exceptional national and local public transportation systems. August is one of the best months to visit. Summer weather is lovely and enables many activities to be experienced within the city, in its surrounding mountains, and across Switzerland.

CALL FOR PAPERS
Engineers, architects, researchers and anyone interested in shell and spatial structures are invited to submit abstracts of 300-400 words in English and participate in IASS 2024.

DEADLINES
- Abstract Submission December 2023
- Full paper submission April 2024
- Acceptance Notification May 2024

Official submission dates to be published in June 2023.

ORGANISING COMMITTEE
- Chairs: Prof. Dr. Philippe Block, Prof. Dr. Catherine De Wolf, Prof. Dr. Jacqueline Pauli
- Symposium Hosts: NCCR Digital Fabrication, ETH Zurich

SOCIAL PROGRAMME
Social events will include a welcome reception, a gala dinner, technical visits, guided tours and other events.

CORRESPONDENCE
Email: info@iass2024.org
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HIERARCHICAL STRUCTURES COMPUTATIONAL DESIGN AND DIGITAL 3D PRINTING

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ABSTRACT

Current advances in construction automation, especially in large-scale additive manufacturing, highlight the vast potential for robots in architecture. Robotic construction is unique in its potential to reproduce highly complex structures. To advance the question of how rapid prototyping techniques are adopted in large-scale 3D printing of forms and structures, this paper presents computational methods for the design and robotic construction of cellular membranes. This research presents a comprehensive morphological model of structurally differentiated cellular membranes based on the theoretical biology model of hierarchical structures found in natural cellular solids, and, more specifically, in trabecular bone. The morphological model originates from a system of forces in equilibrium; therefore, it presents the geometric homology of a static tensional system. This research offers a methodology for the design and manufacture of meso- to large-scale triangulated geometric configurations by discrete design methods that are suitable for the robotic fused deposition of lattices and their architectural implementation in the automated manufacturing of shell structures. First, this paper explores how a form can be digitally created by geometrically emulating a given static system of forces in space. Second, inspired by the complex mechanical behavior of cancellous bone, we apply hierarchical principles found in bone remodeling to characterize discrete units that conform to continuous trabecular-like lattices. We study the geometry, limitations, opportunities for optimization, and mechanical characteristics of the lattice. The computational design methods and additive manufacturing techniques are tested in the design and construction hierarchical structures.

Keywords: hierarchical structures, robotic fabrication, additive manufacturing, structural optimization, lightweight shells, lattice, cellular solids, biomimicry

1. INTRODUCTION

Current advances in computational design and in large scale additive manufacturing (AM) have increased the productivity and performance of building shell structures. Robotic manufacturing methods make way for interdisciplinary research fields around computational design and engineering. Identifying construction elements susceptible to automation is key in these fields.

At the architectural scale, construction automation and AM present a novel production scenario [1], [2], [3] of a promising increase in productivity when building complex surfaces [4]. Moreover, AM offers an unparalleled design freedom to build forms of highly complex mechanical behavior. Merging stress data, and material differentiations to gradually integrate various functions, we explored stress-influenced design methods and their inherent manufacturing constraints for 3D printing.

This research offers an architectural application of the underlying material design strategies of naturally formed patterns found in bone structure. Cancellous bone structure continually adapts to the stress trajectories finding the optimal dissipation of stress.

In this study we elucidate a general design and fabrication method for lightweight hierarchical structures capable of being manufactured by robots continuously on-site or by prefabricated segments assembled into a mechanically continuous complex surface.
1.1. Membrane design and spatial 3D printing

AM generally involves the creation of a series of coordinated, automatic, electromechanic operations and demands the configuration of specialized deposition toolpaths. Spatial 3D printing, a Fused Deposition Modeling (FDM) extrusion-based technology, offers exceptional characteristics for creating complex cellular structures. Spatial 3D printing techniques are increasingly being successfully implemented in the construction of large-scale assemblies [5] demonstrating the vast potential of robots in construction. Recently, Virginia Tech and Nagami Design created a 3D printed lattice for the CaixaForum Valencia central pavilion, an effort that overcame the challenges of applying the technique in a public space (Figure 1).

**Figure 1:** Architectural application of the spatial 3D printing technique: 3D printed lattice designed by Virginia Tech and manufactured by Nagami Design

Automated design and fabrication methods are progressively being applied in the design and construction of complex shapes. This research builds on current studies in spatial 3D printing methods and presents novel algorithmic methods and geometric generalization to robotically fabricate triangulated tessellations that conform complex surfaces. The particularization of models for creating the voxelized approximation of a shape is one method [6], [7], [8] that has allowed designers to defy the layerwise stacking principle of standard AM and allowed the creation of complex spatial arrangements (Figure 2).

**Figure 2:** Spatial 3D printing of a lattice with multiple materials and differentiated polyhedral arrangements

Digital tools in design for fabrication integrate geometric logic of constructability and design goals [9]. The system of particlizing involves a computational discretization of a shape where each particle represents an individually indexed container and value, ordered in space. Sequencing the particles and their geometric information allows a robotic system to fabricate the designs in a linear, additive fashion. This study employs generative and analytical digital tools that create and evaluate triangulated tessellations inspired in the theoretical biology model of cancellous bone reformation.

A key concern we aimed to develop is the criteria by which we can 3D print a large-scale stable shape. We approximated the bone reformation model using static analysis results of a given form in equilibrium to create FEM influenced 3D printed structures.

The methodological process involves characterizing the set of complex surfaces, determined by Bézier curves or the spaces determined by said surfaces. In order to determine stable behavior and define spaces and surfaces of continuous structural behavior, we can configure the geometry by aggregating cellular elements that make up a stable tessellation or lattice in a continuous path of 3D printing (Figure 3).

**Figure 3:** (a) Reference surface and (b) triangulated lattice derived from stress trajectories and additive manufacturing parameters

2. LITERATURE REVIEW

We studied stabilization by triangulation and by application of forces to balance a digital cellular membrane. The paper examines the following:

- Configuration of complex geometric arrangements based on biomechanics
- Digital stereotomy by discrete design
- Cellular membrane design, optimization, and hierarchical mechanical characterization
- Spatial 3D printing and robotic AM methods
2.1. Trabecular membrane force to shape morphological principles applied to large-scale additive manufacturing

Cellular solids (of a volume fraction below 30%) and hierarchical structures (arrangements differentiated by stress concentration and trajectories) are often found in natural fibrous composites remarkably illustrating R. Le Ricolais’ words “the art of structure is where to put the holes”. This generally results in ultralightweight structural members. The interest in configuring complex cellular membranes demands the development of a comprehensive simulation-fabrication morphological method where different skills and disciplines converge to successfully present a model of hierarchically engineered continuous surfaces that follow a system of endogenic and exogenic forces in equilibrium while obeying the principles of 3D printing.

We evaluate the following considerations for the development of an abstraction model that links form configuration to a comprehensive workflow of design-simulation-3D printing:

- Current large-scale AM techniques demand the configuration of custom layerwise and spatial deposition instruments.
- Digitally configured membranes are based on the logic of computation. This logic is fundamentally different from predigital models emphasizing the necessity of creating explicit and implicit models of varying levels of abstraction [10], that result in a digital stereotomy.

This evaluation allows us to create a methodological framework for digital 3D printing (3D printing based on particlizing a form, enhancing the performance by inserting additional information, and concatenating commands of deposition) that can be applied to the stress-informed hierarchical organizations.

Biomimicry involves innovation inspired by nature. As T. Mak and L. Shu argue “biomimetic design examines biological analogies to solve engineering problems” [11]. Morphogenetic and theoretical biology strategies help us create algorithmic principles of complex form generation [12].

Nature provides fruitful examples of algorithmic complexity, manifest in the wide interest and influence of current digital design [13], [14], [15] and automatic construction practices [16], [17], [18]. Nature’s cellular solid materials display geometric arrangements of exceptional mechanical properties [19], [20]. The evolutive association of growth and force in natural systems suggests an optimal response to load conditions. Certain bone microstructures exhibit an ultra-lightweight structure, high stiffness, damage tolerance, controlled energy absorption, and functional robustness [21], properties that are critical to critical toward architectural applications.

The particular interest of this research is drawn from the structural lattices found in cancellous bone [22]. Geometry is the most influential aspect of strength found in very lightweight trabecular architectures found in biological composites [23, 24]. AM technologies have allowed designers to develop novel material arrangements that effectively expand the material property space [25], and design infills patterns that conform very complex structures that are influenced by stress trajectories [26].

Although 3D printing technologies, due to their high precision, open new opportunities to design and fabricate complex structures [27], these studies are generally tested at a small scale. At the architectural scale, the use of natural cellular arrangements as structural components presents design and manufacture challenges of scale and production time. The implementation model capable of following the trajectorial hypothesis of stress in complex cellular arrangements demands the assessment of geometries that follow the principles of digital 3D printing.

2.2. Digital configuration of a cellular membrane

Using discrete methods, we design for additive manufacturing incrementally building complex tessellations of differentiated architectured properties (such as stiffness, strength, and density) configured by the forces in equilibrium that define it. The analysis, identification and generalization of geometries and methods to produce hierarchical fibrous arrangements that comply with the several limiting constraints of a robotic technique of 3D printing demanded the following:

First, the development of algorithms that bridge mechanical analysis information with discrete data structures.

Second, algorithms that bridge the discrete data structures and geometrical configurations capable of originating a mechanically continuous membrane through design and optimization with nonlinear mechanical characterization.
2.2.1. Discrete data structures

The membrane configuration process involves computing mechanical data, interpreting it in an intelligible order and using the information to populate a digitized shape. To illustrate this process, below we describe the analysis of a 23 m x 13 m x 7 m ellipsoid-like shell fixed at the equator, with a variable wall thickness that spans 30 cm at top and bottom boundaries to 50 cm at the equator regions (Figure 4 and 5).

![Figure 4: ParaView visualization of a point cloud showing displacement vectors and von Mises stress values expressed in pascals](image)

![Figure 5: Rhino 3D visualization of a stress region information entered into Grasshopper, the static analysis data is calculated using SimScale and discretized into quantiles using ParaView](image)

Made of a typical polymer 3D printed material, with a 30% volume fraction, we estimate its young modulus (E) to be 80MPa and Poisson ratio (ν) to be 0.38 based on experimental tests [28], [29]. The nonlinear static analysis performed in SimScale [30] and processed in ParaView [31] shows the reaction to its dead load and 600 KN vertical load. In this case, von Mises stress values range from 3.4 to 110 kPa and vectorial displacement values, from 0 to 15 mm. The values are organized as an isostatic point cloud, a large set of values the sum of which define a shape in equilibrium.

Point cloud values are interpreted in Rhino 3D and Grasshopper [32] as stress regions to create a stress-informed shape.

![Figure 6: Structured infill configuration process: discretization of the ellipsoid membrane segment](image)

Geometry and force are linked in a structure design with this method. The discrete design method of multiresolution [33] allows us to define volume out of indexed data containers to create a digitized equivalent model, in the digital version we bridge design, simulation, and fabrication as illustrated by Figure 6.

2.2.2. Space filling polyhedra

The method allows us to determine morphogenetic principles to approximate complex forms, populate space-filling regular tessellations, and incorporate the capacity of 3D printing.

An advantage of using space grids such as regular space filling polyhedral arrays is that each member contributes to the general load carrying capacity and that the spatial arrays can be configured to work under simple stress rather than bending [34].

In other structures, each structural member, such as a beam, must be capable of dissipating concentrated stress when subject to a given concentrated load. Instead, for spatial structures, concentrated loads will be distributed along and throughout the lattice, distributing the stress more efficiently, therefore utilizing less material to carry the same load.

The studies of tetrahedral, semi octahedral and rhombic dodecahedral space filling arrangements in this research (Figure 7) are largely influenced by R. B. Fuller studies on “cubic packing” structures [35].

![Figure 7: Different regular polyhedral arrangements inscribed in an orthonormal grid exhibit geometrical relationships](image)
Certain space filling polyhedral, such as octet trusses, can be used to create tessellations (Figure 8) that populate the orthonormal grid of a discretized membrane to be individually and incrementally 3D printed to constitute a continuous spatial structure.

These arrays create an optimal organization of struts for stress distribution. A. Edmonson [35] succinctly describes the enormous structural potential of geometry when describing Fuller’s octet-truss “we can now appreciate the difference between diamond and graphite. Their organization can be thought of as a double octet truss, two intersecting matrices with the vertices of one overlapping the cells of the other. Stabilized by the high number of bonds between neighboring atoms, which also allow forces to be distributed in many directions at once, the configuration is supremely invulnerable. In contrast, carbon atoms in graphite are organized into planar layers of hexagons, triangulated and stable in themselves, but not rigidly connected to other layers. The comparison provides a spectacular example of synergy: rearrangement of identical constituents produces two vastly different systems”.

2.2.3. Hierarchical differentiation of fibrous arrangements

3D printing is usually divided in two unrelated parts an external perimeter and an internal structure. Structural optimization methods adapting theoretical biology models are increasingly being applied to tailor the internal structure of the 3D print (called infill) by varying material allocation to create foam or dense tessellations [36] [37].

The proposed methodology allowed us to test membranes to work only under simple stress, 3D print cellular membranes with individual characterization of struts, determine their local density, material and shape optimization in segments and as whole membrane structures. Strong yet light, cellular solids, or foams, found in nature exhibit very complex, mechanical performance, with strategic variations they are capable of transitioning from fully dense and highly stiff bodies to very light, energy absorbing configurations (Figure 9).

Inspired in the bone reformation model we distinguished variable mechanical properties depending on density, trabecular architecture, and material. Bone structure presents an optimal porous distribution of mass that is intimately coordinated with the stress to which it is subject. Substantial research effort has been dedicated to comprehending the robust [24], [2], [38] morphogenetic configuration and hierarchical functional adaptation of bone under mechanical loading, since J. Wolff in [39] [40] presented the concept of biomechanical adaptation interpreting the static graphics method by K. Culmann [41], [42].

Bone transformation is a highly coordinated adaptation of the bone tissue, J. Wolff’s stress trajectory hypothesis has been corroborated under relatively simple load FEA studies and is debated as there is currently a lack of consensus on the precise interpretation of stress trajectories in trabecular and cortical bone in complex load scenarios, as discussed by J. Skedros [43]. We are only beginning to understand the mechanical work of bone due to advances in computational models such as analytical discrete methods [44].

Although J. Wolff’s intuition remains a matter of debate, the literature review finds consensus in geometry as the most influential aspect of bone strength, while density, strut orientation and strut material provide the main mechanical characteristics, in that order of importance [23].

The efforts of this research focus on presenting a method to shape a membrane by configuring the forces in equilibrium that define it. Cellular morphologies of different scales exhibit unparalleled
freedom to engineer anisotropy and introduce hierarchical mechanical grading [45]. Optimizing the material distribution by controlling levels of porosity, creating more efficient stress distribution, and inducing stiffer cellular arrangements is key to achieving larger scale constructions as it reduces the weight of the structure and reduces material waste.

Although more limited than other high-resolution printing techniques commonly applied to lattice 3D printing, FDM provides an efficient platform of fabrication, particularly for meso- to large-scale arrangements.

3. METHODS

We explored geometrical potential to spatially vary lattice parameters to accommodate complex loading conditions to localize reinforcement material in regions where tensile loads are projected, thus optimizing material use. First, we perform a nonlinear static analysis simulation of a shell using SimScale and export the results as a point cloud. The scalar and vectorial load scenario results are linked to each sample point. We then process the large amount of unstructured information using ParaView to differentiate stress regions. Finally we import stress regions into Rhino3D and Grasshopper software, where we algorithmically populate the different stress regions with structured hierarchical fibrous arrangements.

The resulting design reconfigures the input solid into a hierarchical membrane emulating the stress trajectories in a force-geometry homology model.

3.1. Force-determined hierarchical membranes

In this research, lattices were designed to extend periodically and by transposition of the geometric arrangements, optimized for minimal deformation (improved stiffness) by allocating the material where it responds to stress and strain. With SimScale and ParaView we produced and postprocess implicit informed data structures. The information included vector and scalar values per sampling point of an unstructured mesh of tetrahedral VTK cells (Figure 10). VTK cells are three dimensional meshes. VTK is an abstract class that specifies the interfaces for data cells and provides data visualization for a variety of grid types. Data cells are simple topological elements such as points, lines, polygons, and tetrahedra of which visualization datasets are composed. Visualization datasets may compose cells explicitly (e.g., vtkUnstructuredGrid), or implicitly (e.g., vtkStructuredPoints).

Cellular membrane engineering with this method involved discretizing the surfaces into ordered, indexed particles. To create sequential 3D printing commands, the particles were organized in a linear list of rows, columns, and levels [33].

Indexing allowed us computational access to the particle level, and offered a tool to fabricate a highly intricate, customized structure (Figure 11). Each particle that composes a digital mockup can host an indeterminate amount of information allowing us to individually allocate properties to create complex geometric arrangements inspired on biomechanics.

We differentiated each particle according to the stress regions they belong to and populated the indexes with lightweight polygonal arrays that improve stress distribution (Figure 12).
The process of design transfers a data point cloud stress field to geometry, transferring differentiated characteristics from the whole to the level of the part. The geometric definition of each cell or particle depends on the general conditions of equilibrium. The key aspects of the workflow proposed is its capacity of AM generalization and its potential to automate the geometric configuration mimic bone formation applying:

- Variable volume fraction properties
- Variable strut architecture properties
- Variable material properties

Each segment of the lattice must comply with the constraints of the robotic 3D printing process [46]. This characteristic proves their capacity to be fabricated with large-scale 3D printers or robotic mechanisms, on-site or by prefabrication.

### 3.2. Characterization workflow summary and implementation

The toolpath creation method was principally aimed at being able to access every portion of the linear additive process to be able to examine and determine its characteristics individually.

The difference from other methods of force influenced form configuration is that this method accessed and interpreted the information of a point cloud, three dimensionally, and discretely throughout the solid.

We computed the stress values using SimScale, the software discretizes a solid into tetrahedral VTK cell samples for static analysis; the results were exported to OpenFoam format [47]. Other software such as Elmer FEM [48] capable of calling ParaView or exporting cloud point can be used. With ParaView we postprocessed the vector and scalar information data sets and to exported a simplified set to Rhino3D-Grasshopper in the form of lists and brep stress regions. We then interpreted the cloud of forces in the 3D modeling software using parametric tools, finding a particularization resolution that balanced shape fidelity, and computational power.

Figure 13 illustrates the intensification of trabecular arrangements in two levels of variable resolution and variable thickness. The computation of a stress field and the hierarchical configuration of lattices operated at two levels: the general voxel resolution by the incremental subdivision of cells and the intensification of areas according to stress.

Figure 14 illustrates the four steps we performed to characterize lattices: (a) an isostatic cloud that contains scalar and vector stress information is computed; (b), discrete units of geometry linearly aggregate into a continuous cellular membrane influenced by the stress field, density variation, trabecular architecture, and material configuration create a mechanically complex fibrous arrangement; (c) the characteristics of individual struts is determined by differentiated electromechanical commands of spatial 3D printing, to vary its specific architecture; and (d) a hierarchical membrane shape is incrementally built.
3.3. Generalization of triangulated lattices for digital 3D printing

We defined the principles of 3D printing triangulated lattices and cellular structures with this method. We created parametric algorithms able to fabricate continuous complex forms serialized in 3D printable structural components.

3.3.1. Digital 3D printing

Digital 3D printing infers the existence of a digitized equivalent model to which the fabrication technique is applied. It infers the existence of intelligible data in the model to be printed and presents a continuous method of analytical data processing from raw data into usable form into instruction [49].

In a regular 3D printing processes with standard 3D printers, the fabrication file is first generated by converting the model into an STL file format (an abbreviation of stereolithography). This process describes a given geometry in a raw, unstructured triangulated surface by the unit normal and vertices of the triangles using a three-dimensional Cartesian coordinate system. A 3D printing generator, called slicer, takes a given STL file and generates a G-Code file (i.e., the instruction language used by 3D printers) to produce the 3D modeled object.

Instead, digital 3D printing consists first, of the digitization process that structures a model into sequenced indexes with information, and second, the definition of the commands definition to materialize each index. The fabrication toolpath will process and actuate commands linearly for the z, x, and y indexes of each coordinate, in that order.

Using digital 3D printing we fabricated the fibrous arrangements that approximate a discretized membrane within an orthonormal hexahedral reference grid. The fabrication instrument form factor limited the geometric freedom of the fibrous arrangements. We used a custom a nozzle to test the 3D printing of the fibrous arrangements. Compared to a standard nozzle design, the elongated custom nozzle maximized the design freedom (Figure 15).

The lattices were generated using two inputs: the solid membrane to be converted onto a hierarchical structure and the point cloud to extract information from. Different geometrical arrangements yield very different mechanical behavior effectively emulating the characteristics of foams and dense solids; density variations in cellular solids gradually modify elastic moduli to display increased stiffness or sponginess to control energy absorption as desired [28].

Figure 15: 3D print instrument general components and adjustment, nozzle characteristics

Translating polylines first to sequential target points and then to fabrication codes, we extracted the coordinates that create polygonal arrangements and sorted these into types referring to their requirements of deposition. This helped us determine the correct speed, flow, and cooling deposition commands. We exported the information as G-Code and Rapid code using a python script that applied the conditions of 3D to the spatial lattice generalization [50]. Four kinds of points, each with a unique set of electromechanics commands, were identified to describe any given tessellation to be 3D printed with this method (Figure 16).

Figure 16: Categorization of points in polygonal lattice arrangements for spatial 3D printing

The foundation of the lattice required increased flow and no cooling system to ensure a strong contact with the base; points in mid-air that had not been created priorly required cooling systems to vitrify the segment in space; repeated points that had been created before highlight the creation of a knot and
require slow approximation motions, higher flow and no cooling to ensure bonding; and lastly points at the end of a segment require to remove the nozzle out of the lattice to avoid collisions with priorly deposited material, as illustrated by Figure 17.

Figure 17: Side view diagram displaying types of polylineal lattice for spatial 3D printing

3.3.2. Triangulated spatial filling arrays

The polyhedral arrays are configured to approximate the mechanical behavior found in the theoretical biology model and stress trajectory theory of bone formation. According to J. Chilton [34] “the stability of rigid jointed space frames depends on the bending resistance of the joints for its structural integrity. However, space truss structures depend on their geometrical configuration to ensure stability.

To form a stable truss structure composed of nodes interconnected by axially loaded bars only, a fully triangulated structure must be formed.” Maxwell’s equation of equilibrium in a three-dimensional space structure determines tetrahedra as the minimal unit of a lattice. Additionally, if a structure is not fully triangulated, from the equation follows that stability can be achieved by additional external struts.

Tetrahedral lattices and other spatial tessellations in certain types of filling arrangements can follow a square pyramidal segmentation (Figure 18).

Figure 18: Polygonal lattice printability based on the square pyramid rule

This characteristic determined that we can always print a segment of a face of the polyhedral array with three target points that create a triangle, base in the bottom, apex on the top, to assemble a face of the pyramid segmentation.

Tetrahedral octahedral 3D infills are among the most extensively studied spatial arrangements due to their mechanical properties. Studies are more commonly found as small-scale lattice structures, built at the meso scale with layerwise systems, and out of planar aggregated planar segments with snap fit designs achieving architectured material properties [51].

In this research we studied orienting the direction of the fiber and deposition along each strut member to test the generalization method proposed and extend the technique to large-scale assemblies in continuous structural surfaces configured as hierarchical cellular membranes using regular polyhedra.

The spatial arrangements we studied for digital 3D printing include tetrahedra, octahedra, rhombic dodecahedra, truncated cuboctahedra, and combined polyhedral arrays.

The lattices were created starting from one end of the lattice defined as base and incrementally growing by attaching struts. Preferably the first line to deposit is a horizontal foundation to create greater grip for the subsequent targets that create a triangle in space. The omni symmetrical qualities of and uniform dispersion of points certain regular tessellations allow for a geometrical arrangement of a single type of triangle to conform to all faces of the polyhedral array simply by a mirror transformation along row and column order, always shifting one unit in the next shifting floor order (Figure 19).

Figure 19: Tetrahedral octahedral toolpath configuration describing deposition segments in black, and traveling segments in blue

The main aspect to ensure printability when choosing and configuring the tessellation is the capacity to build it out of a concatenation of square pyramids with apex at the top.

The square pyramid principle allows the 3D print tool to navigate the space without intersecting with previously deposited material and to incrementally
build a membrane by deposition. The triangular generalization of lateral faces of polyhedral arrays creates a continuously additive process of square base pyramid formations. Open polygons create very weak links and the vitrification time they require to form makes them difficult to print with enough accuracy.

The lattice is built by recreating triangular faces of the intercalating tetrahedra, which leave an open volume area to reconfigure the path of deposition depending on the position of the triangle in space. The triangulation needs any of two base points to begin the construction form as depicted in the diagrams. This feature allows us to create overhanging structures. To ensure freedom of movement of the nozzle, the square pyramids must be compliant with the tape angle of the deposition system. For example, for a 45-degrees nozzle taper, the square pyramid must simply be composed of congruent isosceles triangle angles. Square pyramid characteristics determine the manufacturability of a given regular polyhedral lattice.

Location in quadrants will determine its direction of print. The quadrant differentiation produced by the row, column, level order of print is bypassed by printing lateral faces of pyramids left to right, or top to bottom, depending on the quadrant in which the unit is located. Otherwise, the first initial point of a print segment of deposition of the lateral triangle would be freely located in space, without a structure to attach to.

In summary the main characteristics that determine the manufacturability of tessellations configured by the square pyramid segmentation method were as follows:

- Slant angle of the pyramid < taper angle
- The total height of a segment must be free from nozzle and other 3D print system obstructions
- For small taper angles, scaling the tessellation in height to clear slant angles will allow nozzle systems adequately 3D print in space

4. RESULTS AND DISCUSSION

In the workflow studied, the principles behind the morphological configuration of forms relate not only to stress and load as in topology optimization methods, but it also to a homology concept that continuously characterizes the geometric constraints, and the forces that shape them.

According to the concepts presented, any change in the system of forces that determines a stable form automatically and necessarily reshapes the fibrous arrangement. The methodology allowed us to determine the efficient material distribution of cellular solids and their manufacturability by additive methods. In the theoretical biology model density variations along principal stress lines optimally distribute tensions throughout the cellular solid. The hierarchical structures of nature remain homologic forms of the tension that shape them as geometrical expressions of force. Akin to the process of remodeling found in bone tissue, we used the stress trajectories that determine hierarchical designs to propose a homology model of line of force and geometrical arrangements. By rearranging polyhedral arrays and differentiating each segment we can configure functionally graded solids with improved mechanical qualities.

In terms of manufacturability, the hypothesis demands a technical configuration of force influenced membrane design that proves the capacity to compute variable strength modulus and elastic moduli solely with variations in density, orientation, and material, using the electromechanical means of deposition (numerical positioning, extrusion rate, extrusion angle). Tetrahedral-octahedral and rhombic-dodecahedron tessellations were found to provide very stable organizations for FDM spatial 3D printing.

Figure 20: (a) Polyhedral array model and (b) FDM 3D print test exhibiting geometric and density variations

Figure 21: Meso-scale FDM 3D print test of a rhombic-dodecahedron tessellation
The triangulation of the cellular arrangement distributes applied forces efficiently across a gridshell. We tested printing different polyhedral arrays with commercial FDM printers and robot arms equipped with custom extrusion mechanisms (Figure 20 and 21). We controlled individual strut thickness by incrementally depositing more material repeating a segment or using unique electromechanical commands, changing speed-flow correlation.

In terms of design, this research processes the information in a force field, making it explicit as geometry instantiations. The design methods presented in this paper were tested in a large-scale study of a potential application of the resulting structures (Figure 22). Employing the methodology to an alternative design of “La Nube”, we controlled every part of the material network so that the individual unit’s value is related to the value of the whole. The hierarchical structure was digitally assembled discretizing the ellipsoid onto 16,800 indexes, ordered in a 3D printable sequence. Indexed voxels were populated with polygonal shapes according the stress quartile they belong to.

![Figure 22: Hierarchical structure concept applied to the computational design of a 3D printed shell, proposal for La Nube: (a) exterior view; (b) interior view](image)

The distribution and orientation of fibers were algorithmically chosen to vary volume fraction and architecture of the shell to populate low to high stress regions. 174 km of robotic toolpaths build the shape, of which traveling sequences are one-third and material deposition sequences are two-thirds. Using PETG as feedstock, the total weight of the structure would be approximately 9,620 kg.

Hierarchical membrane designs display a very high mechanical performance with a very low weight. Form-function hierarchical relationship in the examples presented are derived and prioritized from stress trajectories, resembling the adaptability and biomechanics of cancellous bone.

The methods presented require high computational power. Due to computational demand limitations, the design studies were restricted to a simplified interpretation of the model based on 4 stress regions.

Future work involves the creation of algorithms that can efficiently compute force and geometry homology models in a higher resolution potentially creating unique architecture, volume fraction and material solutions for each particle of the force field.

Although this research studies the application of spatial 3D printing and FDM, the methods described here are not limited to 3D printing with thermoplastic polymers. AM applications in construction are increasingly advancing towards larger scale applications and high strength materials. The computational design workflow automates the generation of cellular design following strict geometric rules. Current developments in AM setups cable robotics [52] and wire arc additive manufacturing [53] encourage us to visualize the large-scale application of hierarchical design methods with higher strength materials in the future.

5. CONCLUSION

The paper discusses the application of digital 3D printing to the production of complex geometries capable of assuming a continuous shell structural behavior, whose definition and computational design is based on a trabecular system. We propose a comprehensive morphological model of hierarchical fibrous structures. Functionally graded cellular structures found in nature display high mechanical capacity, stiffness, damage tolerance and ultra light weight. We make use of the additive manufacturing’s robotic precision advantages to design and build complex cellular arrangements.

We approximated the biomechanical characteristics of cancellous bone remodeling following its morphogenetic logics in response to respond to external loading conditions to define hierarchical structures. The morphological principle was integrated into a comprehensive workflow of computational design and multicriteria optimization. First, an isostatic cloud that contains scalar and vector stress information was computed and categorized into quartiles. Second, discrete units of geometry are mechanically characterized and linearly aggregated into a continuous cellular membrane influenced by the stress field. Third, each lattice segment is categorized for 3D printing using unique electromechanical commands.
The methodology developed allowed us to study the characterization of a hierarchically organized cellular membrane, and to establish the general design characteristics that ensure the digital manufacturing of hierarchical free-form structure.

The studies center the definition and computational design of complex surfaces as well as the respective construction of these shell structures by means of robotically printed three-dimensional tessellations, capable of configuring mechanically continuous complex surfaces, based on a comprehensive morphological workflow, which yield extraordinary ultralightweight structures. The method proposed offers a force-geometry homology model.

We proposed a method to characterize trabeculae networks of fibers configured by a static system of internal forces. We studied the principal aspect that influences the strength of cellular structures in trabecular arrangements and geometry. We applied and verified the mechanical gradation capacity of the system. We modified the trabecular architecture reallocation mass strategically. We increased the density where stress is concentrated and along tension trajectories to improve the mechanical characteristics of the cellular structure. We presented a systematic organization method of very large amounts of data that merge within a form to create a cellular membrane. We defined hierarchical design as the process of structuring geometric arrangements into continuous structural surfaces as a function of force trajectories and stress values.

This research offers a general method for designing and 3D printing hierarchical structures. We tested and evaluated the serialized fabrication of different space filling polyhedral arrays to assess their potential to conform hierarchical structures. Tetrahedral, octahedral, and rhombic-dodecahedron tessellations were found to provide the most appropriate geometric organizations and mechanical qualities for a lightweight FDM technology.

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DATA AVAILABILITY

Some or all data, models or codes that support the finding of this study are available from the corresponding author upon reasonable request.

REFERENCES


[32] Rhinoceros 3D. (7), Mc Neel & Associates


STUDY THE INFLUENCE OF GRID-JUMPING LAYOUT ON SPATIAL CABLE-TRUSS STRUCTURE WITHOUT INNER RING CABLES WITH RUPTURE OF LOCAL CABLES (STRUTS)

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ABSTRACT

Spatial cable-truss structure without inner ring cables (SCSWIRC) is a new type of cable-truss tension structures (CTTS), and its anti-collapse ability is strong, but its construction forming is difficult. The main reason is that there are a lot of struts (or compression struts) when the span of SCSWIRC is larger and struts are easy to cause winding and collision during its construction. In order to solve the difficulty of construction forming, the grid-jumping layout was proposed to simplify SCSWIRC to delete the redundant struts. It is necessary to further study whether the anti-collapse ability of the remaining structure after the grid-jumping layout is affected by grid-jumping layout. Based on transient dynamic theory, the rupture of local cables (struts) of SCSWIRC with grid-jumping layout is studied. The research results show that self-weight has a little influence on the SCSWIRC; the initial prestress only increases the internal forces of components and the same proportion of feasible prestress levels do not amplify the response of SCSWIRC with rupture of local cables (struts); the anti-collapse ability of the remaining structure after the grid-jumping layout of SCSWIRC is still strong and the ability to resist the external loads is good at the same time. The rupture of local cables (struts) for the original scheme and grid-jumping layout schemes do not cause the progressive collapse. The research contents offer useful reference for the safety design of SCSWIRC.

Keywords: Spatial cable-truss structure without inner ring cables (SCSWIRC); The rupture of local cables (struts); Progressive collapse; Grid-jumping layout; Transient dynamics theory

1. INTRODUCTION

It is common to see the local damage or the whole progressive collapse of the structure caused by the failure of a single structural member. Due to the serious damage caused by structural collapse to society and citizens, more and more scholars focus on the research field of structural anti-collapse, but most of the research results are limited to the field of frame concrete structures [1]. For example, the progressive collapse of the corner structure of the Ronan Point Apartment Building in London first attracted the attention of the government and researchers on the study of the progressive collapse of structures [2]. The collapse of the Federal Building in Oklahoma in 1995 and the Twin Towers of the World Trade Center in 2001, following the terrorist attacks, refocused the attention of the construction and engineering community on structural collapse [3]. In recent years, the partial or whole collapse of large public buildings has become increasingly prominent, such as the roof collapse of the Waiting Hall at Charles De Gaulle Airport in France in 2004, the collapse of the Bart Reichenhall Skating in Germany in 2005, the collapse of the roof of Bormann Market in Moscow in 2006 and many practical engineering collapse accidents [4].

Although the achievements of anti-collapse analysis are more and more in the world [1,5-8], the anti-collapse problems of large-span spatial structures have not attracted much attention from researchers because of the limited use of large-span spatial structures and few collapse accidents. The existing
The anti-collapse of flexible tension structures is mainly concentrated in cable-strut tension structures, which mainly includes cable dome structures, spoke cable-truss structures and spatial cable-truss structure without inner ring cables [19]. Such as, He J, et al. [20] studied the cable dome structure with rupture of local cables, and obtained that the ring cables had a greater influence on it. Gao Z Y, et al. [21] carried out the anti-collapse analysis of rigid bracing dome and obtained the important coefficient of all kinds of components and ranked the importance of components. Tian G Y, et al. [22] studied the anti-collapse analysis of spoke cable-truss structure and found that the whole structural failure could be caused by the rupture of inner ring cables. Huang H, et al. [23] studied the anti-collapse analysis of the whole cable-membrane spoke cable-truss structure.

Spatial cable-truss structure without inner ring cables (SCSWIRC) is a new type of cable-truss tension structures, which evolves from spoke cable-truss structure and is mainly composed of upper and lower single layer crossed cable nets and middle compression struts [19,24]. But SCSWIRC still stays in the stages of theoretical and experimental research, and there is no application of engineering. The literature [25] has proved that SCSWIRC has strong anti-collapse ability, but the construction forming of SCSWIRC is difficult. The main reason is that when the span of SCSWIRC is large, the number of struts is too large and its length is too long. In the construction forming process, the struts and the upper and lower single layer crossed cable nets will have serious winding and collision phenomena [26]. In order to solve the difficulty of the construction forming of SCSWIRC, the Ref. [26] proposed to simplify the structural system by using the grid-jumping layout to remove the redundant struts, so as to reduce the construction forming difficulty of SCSWIRC. The Ref. [26] proved that the grid-jumping layout is able to simplify SCSWIRC. However, since the topological relationship of SCSWIRC has changed after the removal of the redundant struts, further study is needed to determine whether SCSWIRC still has sufficient anti-collapse ability to resist external loads after grid-jumping layout.

Based on the transient dynamics theory [20], the paper uses the universal Finite Element Software ANASYS to simulate the faulted cable (strut) of SCSWIRC and the complete transient method in
ANSYS software can accurately simulate the nonlinear problem of SCSWIRC. Firstly, the paper studies the influence of the self-weight on SCSWIRC after rupture cables (struts). Then the influence of the feasible prestress level on SCSWIRC after rupture cables (struts) is studied. Then the influence of the external load on SCSWIRC after rupturing cables (struts) is studied and the whole process of the time-history response analysis of rupture cables (struts) is also studied. Finally, the conclusions of the paper are given.

### 2. STRUCTURAL MODEL

The structural model of the paper is the same as the structural model from Ref. [26], and SCSWIRC is also called Annular Crossed Cable-truss structure (ACCTS). In order to eliminate the influence of the deformation of the ring-beam and supported column on the prestressed state of SCSWIRC, the stiffness of the ring-beam is assumed to be infinite. Namely, the influence of ring-beam’s stiffness on SCSWIRC is not considered. The specific parameters of SCSWIRC are as follows: the span of SCSWIRC is 100m shown in Fig. 1(a); the ring equivalent fractions are 15, namely, SCSWIRC is composed of the same 15 planar cable-truss frames in the weave and crossed way; the detailed size of a single planar cable-truss frame is shown in Fig. 1(b). C stands for cables and S stands for struts (or compression struts). The elastic modulus and density of cables are 1.38×10^5 MPa and 7.85 g/cm^3, respectively; the elastic modulus and density of struts are 2.06×10^5 MPa and 7.85 g/cm^3, respectively. The cross-sectional areas and structural feasible prestresses of structural components are shown in Table 1.

### 3. INFLUENCE OF SELF-WEIGHT AND DIFFERENT PRESTRESSED STATES ON THE ORIGINAL SCHEME WITH RUPTURE CABLES (STRUTS)

#### 3.1 The influence of self-weight on the original scheme with rupture cables (struts)

The original scheme is shown in Fig. 1. In Fig. 1, the C1 to C5 are the lower chord cables of SCSWIRC, and the C6 to C10 are the upper chord cables of SCSWIRC, and the S1 to S4 are the struts of SCSWIRC. When the prestress is P in Table 1, the positions of rupture cables (struts) are on the C1 to C10 and S1 to S4. The calculation results of internal forces of cables and struts and the nodal displacements in the original scheme are shown in Fig. 2 and Fig. 3.
From Fig. 2, the structural self-weight has little influence on the internal forces of cables and struts and the nodal displacements after SCSWIRC ruptures the cables and struts. From Fig. 2(a), the maximum internal force of the cables is located on the C6 without self-weight and the maximum value is 454.161 kN; the maximum internal force of the cables is located on the C6 with self-weight and the maximum value is 442.215 kN; with or without self-weight, the internal force difference of the rupture cables (struts) is 2.63%. From Fig. 2(b), the maximum internal force of the struts is located on the C4 without self-weight and the maximum value is -41.876 kN; the maximum internal force of the struts is located on the C4 with self-weight and the maximum value is -43.574 kN; with or without self-
weight, the internal force difference of the rupture cables (struts) is 3.99%. From Fig. 2(c), the maximum nodal displacement is located on the S4 without self-weight and the maximum value is 0.674 m and its position is shown in Fig. 3(a); the maximum nodal displacement is located on the S4 with self-weight and the maximum displacement is 0.639 m and its position is shown in Fig. 3(b); with or without self-weight, the nodal displacement difference is 0.035 m before and after the rupture cables (struts). Meanwhile, it can also be seen that only local nodal displacements are 0.679 m and 0.639 m and most nodal displacements are less than 0.5 m after rupture cables (struts), which meets the allowable displacement value $\sigma = l/200 = 0.5$ m ($l$ is the structural span) in the Technical Specification for Cable Structures [27]. Besides the maximum internal forces and maximum nodal displacement, the influence of other rupture cables (struts) on the internal forces of components is within 8% and the influence of other rupture cables (struts) on nodal displacements is within 0.059 m, which illustrates that self-weight has little influence on SCSWIRC with rupture cables (struts). The main reason is that SCSWIRC belongs to the tensegrity structures system and the self-weight of per unit area for the kind of structures is light, so the self-weight of SCSWIRC can be ignored in the actual analysis of rupture cables (struts).

From Fig. 2(c) and Fig. 3, the nodal displacement of the S4 suddenly becomes larger after rupture S4 and exceeds the allowable displacement value $[\sigma] = 0.5$ m in the Technical Specification for Cable Structures [27], and the other nodal displacements are within the allowable values. The main reason is that the cable forces of the upper and lower chord cables on the S4 are large and the rupture S4 will have a great impact on the upper and lower nodes of the S4. Therefore, the cross-sectional area of the S4 should be enlarged in the scheme design to prevent the rupture of the S4 before the rupture of the other struts S1 to S3.

3.2 The structural responses of rupture cables (struts) under different prestressed states

According to Section 3.1, the initial feasible prestress of the original scheme is $P$. In Section 3.2, the responses of the structure under the five feasible prestressed states are studied when the feasible prestresses of the structure are $0.8P, 0.9P, 1.0P, 1.1P, 1.2P$. When the positions of rupture cables (struts) are on the C1 to C10 and S1 to S4, the change curve of internal forces of cables and struts and nodal displacements under five feasible prestressed states are shown in Fig. 4.

From Fig. 4, the maximum internal forces of components and the nodal displacements under five prestressed states increase continuously and

![Figure 4: The influence of different prestressed states on the internal forces and nodal displacements of the original scheme with rupture cables (struts)](image)

significantly after rupture cables (struts). Namely, the larger the feasible prestress is, the greater the internal forces of all components are, and the more significant the response of all components is. Therefore, the structural feasible prestress level in the design stage should be reduced as far as possible under the premise of meeting the corresponding requirements of Code, so as to reduce the damage caused by rupture cables (struts). Does the multiple increase of the feasible
prestress level multiply the relative changes of the components’ internal forces and nodal displacements after rupture cables (struts)? Therefore, it is necessary to study that issue, and the research conclusions are shown in Section 3.3.

3.3 The amplification effect of SCSWIRC with rupture cables (struts) under different prestressed states

The variation of the internal forces of various components after rupture cables (struts) is studied under the five feasible prestressed states of 0.8P, 0.9P, 1.0P, 1.1P, 1.2P. The maximum internal force obtained after rupture cables (struts) is assumed as N₁, and the maximum internal force of the corresponding member under the feasible prestress is assumed as N₂, therefore the variation of the internal forces is 100 × (N₁ - N₂)/N₂. The main concern is whether the internal forces of all components after rupture cables (struts) exceed the minimum breaking strength of cables or the critical buckling load, so the variation of the internal force after rupture cables (struts) is given in different prestressed states, and the calculation results are shown in Fig. 5.

From Fig. 5, the variation of internal forces of components is basically the same before and after the rupture of cables (struts), indicating that different prestress levels only affect the actual internal forces of the struts and the influence range is about 0.6% to 2%. Therefore, the rupture of cables (struts) has little influence on the variation of internal forces of struts and the influence of the rupture of cables (struts) on SCSWIRC can be ignored to simplify the calculation.

4. THE INFLUENCE OF GRID-JUMPING LAYOUT ON SCSWIRC WITHOUT RUPTURE OF CABLES (STRUTS)

The three-dimensional diagram of SCSWIRC is shown in Fig. 1(a), and the corresponding planar layout diagram is shown in Fig. 6. The grid-jumping layout refers to removing the struts at the inner ring 1 to inner ring 3 in Fig. 6. Namely, the struts at the inner ring 1 to inner ring 3 are removed and then form the new complete structural system, so the grid-jumping layout is different from the rupture of cables (struts). Since the virtual inner ring in Fig. 6 determines structural drainage slope, the lighting requirements and the line of sight of the audience, the struts at the virtual inner ring are not removed by grid-jumping layout. When the struts at the inner ring 1 to inner ring 3 are handled by grid-jumping layout, the corresponding grid-jumping layout schemes are grid-jumping layout scheme 1, grid-jumping layout scheme 2, grid-jumping layout scheme 3, respectively. The grid-jumping layout scheme 1 to 3 is also called scheme 1, scheme 2 and scheme 3, respectively.
schemes (original scheme, scheme 1, scheme 2 and scheme 3) under the initial prestress state is studied in the following analyses. The change laws of the internal forces of cables and struts and nodal displacements for SCSWIRC with the rupture of cables (struts) under the initial feasible prestress $P_f$ are shown in Fig. 7. The discontinuity in Fig. 7 is the position of grid-jumping layout.

![Figure 7: Internal forces of components and nodal displacements for four schemes with rupture of cables (struts) under the feasible prestress $P_f$](image)

From Fig. 7(a) and Fig. 7(b), the internal forces and nodal displacements after the rupture of the upper chord cables are greater than those of the rupture of the lower chord cables. Namely, although the upper chord cables are stable cables, they play an important role in the prestressed state.

4.2 Study the rupture of cables (struts) of four schemes under the loading state

According to the structural model in Section 2, based on SHELL 154 element, the triangular mesh and quadrilateral mesh formed by the upper chord cables of SCSWIRC are used to establish the virtual membrane surface (the virtual membrane surface only transfers load and does not participate in the calculation), and then the uniform surface load of 0.6 kN/m^2 is applied to the virtual membrane surface and constraints are imposed on all lower nodes of SCSWIRC. The obtained support reactions are the vertical equivalent nodal load of all lower nodes of SCSWIRC. The values of all different equivalent nodal loads include: $F_{p1}=-12.42$ kN, $F_{p2}=-22.88$ kN, $F_{p3}=-47.95$ kN, $F_{p4}=-86.57$ kN. The minus sign indicates that the direction of load is vertically downward. The total load on SCSWIRC is $F=15\times[F_{p1}, F_{p2}, F_{p3}, F_{p4}]$. The rupture of cables (struts) of four schemes under external load $F$ is studied. The external load is divided into full-span load and half-span load. The full-span load refers to applying the external load $F$ to SCSWIRC and the half-span load refers to applying the external load $F/2$ to SCSWIRC.

4.2.1 Under full-span load

Although the internal forces of cables and struts of four schemes have certain differences under the full-span load $F$, the change laws are basically the same. Meanwhile, since there are a large number of elements and their change laws under full-span load are basically the same, take the C1 and S1 as the example and the calculation results of the rupture of the C1 and S1 under hieratical loading are given. The results are shown in Fig. 8.
It can be observed from Fig. 8 that under full-span load, the change law of the maximum internal force and nodal displacement of components are basically the same before and after rupture cables (struts). The different point is that the nonlinearity of scheme 3 is larger than those of original scheme, scheme 1 and scheme 2. In Fig. 8(c) and 8(f), the change curves of nodal displacements of scheme 3 shows that the change curve of nodal displacement in scheme 3 is the same as an arc. The change law of other components is the same as those of C1 and S1, and the different point is that the internal forces of the upper chord cables decrease gradually with the increase of the external load while the internal forces of the lower chord cables decrease gradually.

Meanwhile, the response of the rupture cables (struts) of scheme 3 is larger than those of scheme 1 and scheme 2. The maximum nodal displacement exceeds the allowable displacement value $\sigma=0.5$ m in the Technical Specification of Cable Structures [27]. The maximum displacement is -0.723 m when rupturing cable C5; The maximum cable force is 678.256 kN at the same time and the minimum breaking strength of cable is 1794.78kN. The minus sign indicates that the direction is vertically downward, the same below. The maximum pressured force is -46.918 kN when rupturing the S3 and the maximum pressured stress is -15.24 MPa and the allowable stress value is 210 MPa. Under full-span load, the statistical results of the maximum response of four schemes before and after rupture of cables (struts) are shown in Table 2.

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From Table 2, the maximum internal force of cables (678.256 kN) does not exceed the minimum breaking force of cable (1794.78 kN) of the selected cable before and after rupture cables (struts) of four schemes, and the maximum pressured force of struts does not exceed the maximum allowable pressured stress (210 MPa). Before rupture cables (struts), the maximum displacements of four schemes, except scheme 3, do not exceed the allowable displacement value ([σ]=0.5 m) in the Code [27]. After rupture cables (struts), the maximum displacement of four schemes exceeds the allowable displacement value in the Code. The maximum displacement appears in scheme 3 when rupturing the S3 and its value is -0.723 m. But the maximum displacement value is still within the acceptable range. The results illustrate that the remaining structural ability to resist the rupture cables (struts) is still strong and further reveal the original structure has better security reserve function and has better ability to resist the external loads. The results also illustrate from the side that the original structure does have larger redundancy, and the grid-jumping layout can be used to simplify SCSWIROC to remove the redundant components and simplify the structural system.

From Table 2, after the rupture of cables (struts) for four schemes, the remaining structure under the external load generally has the largest force on the cable segment adjacent to the position of the rupture cables (shown in Fig. 9(a)), and the absolutely maximum value of struts is located on the other circle of struts adjacent to the rupture struts (shown in Fig. 9(b)). The maximum displacement is obtained on the position of rupture struts at the same time. The rupture cables (struts) only cause the internal forces of cables and struts and nodal displacements at the local position near the rupture cables (struts) to change greatly, and have little influence on the rest part of the structure. The structural response caused by other rupture cables (struts) can be obtained by analogy.

Table 2: The response results of four schemes before and after rupture cables (struts) under full-span load

<table>
<thead>
<tr>
<th>Data type</th>
<th>Original scheme</th>
<th>Grid-jumping layout scheme 1</th>
<th>Grid-jumping layout scheme 2</th>
<th>Grid-jumping layout scheme 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No rupture cables (struts)</td>
<td>Rupture cables (struts)</td>
<td>No rupture cables (struts)</td>
<td>Rupture cables (struts)</td>
</tr>
<tr>
<td>Max. internal force of cable (kN)</td>
<td>490</td>
<td>590.184</td>
<td>491.346</td>
<td>605.249</td>
</tr>
<tr>
<td>position</td>
<td>C5</td>
<td>C2</td>
<td>C5</td>
<td>C5</td>
</tr>
<tr>
<td>Position</td>
<td>S4</td>
<td>S3</td>
<td>S4</td>
<td>S4</td>
</tr>
<tr>
<td>Max. nodal displacement (m)</td>
<td>-0.337</td>
<td>-0.655</td>
<td>-0.334</td>
<td>-0.653</td>
</tr>
<tr>
<td>Position</td>
<td>S4</td>
<td>S4</td>
<td>S4</td>
<td>S4</td>
</tr>
</tbody>
</table>

Figure 9: The distribution of internal forces of cables and struts and nodal displacement after rupture cables (struts)
4.2.2 Under half-span load

Although the internal forces of cables and struts of four schemes have certain differences under half-span load $F$, the change laws are basically the same. Take the C1 and S1 as the example and the calculation results of the rupture of the C1 and S1 under half hierarchical loading are given. The results are shown in Fig. 10.

From Fig. 10, under half-span load, the change law of internal forces and nodal displacements for four schemes before and after rupture cables (struts) is basically the same as the change law under full-span load. Under half-span load, the different point is that the internal forces of struts gradually decrease with the increase of the external load before the rupture of cables (struts) and the internal forces of struts gradually increase with the increase of the external load after the rupture of cables (struts). But under full-span load, the internal forces of struts gradually decrease with the increase of the external load before and after the rupture of cables (struts). Therefore, the half-span load is more unfavorable to SCSWIRC, and it is easier to cause strength failure or buckling failure of struts. Under half-span load, the maximum response results of four schemes are shown in Table 3.

It can be observed from Table 3 that under half-span load, the maximum internal force of cables pressured stress (210 MPa) before and after the rupture of cables (struts) of four schemes. Before the rupture of cables (struts), the maximum (664.092 kN) does not exceed the minimum breaking strength cable of the selected cable (1794.78 kN) and the maximum pressured force (-51.385 kN) does not exceed the maximum allowable displacements of scheme 2 and scheme 3 exceed the allowable displacement value $\sigma = 0.5 \text{ m}$ and the maximum displacements of the original scheme and scheme 1 do not exceed the allowable displacement value $\sigma = 0.5 \text{ m}$. After the rupture of cables (struts), the maximum displacements of four schemes all exceed the allowable displacement and the maximum displacement appears in scheme 3 when rupturing C5 and its value is -1.104 m. The displacement change of the other schemes is still within the acceptable range except that the displacement of scheme 3 is large under the half-span load. The analysis results show that the remaining structure has a better ability to resist the rupture of cables (struts) after the original scheme with grid-jumping layout, which also reveals that the original structure has a better safety reserve function and has a better ability to resist the external loads.

Meanwhile, it can be known by comparing Table 2 and Table 3 that the internal force values and nodal displacement values of four schemes have been changed by half-span load before the rupture of cables (struts), but the positions of the maximum internal forces and maximum displacement haven’t changed by half-span load. After the rupture of cables (struts), the internal force values and nodal displacement values of four schemes not only have been changed by half-span load, but also the positions of the maximum internal forces and maximum nodal displacement have been changed by it. Meanwhile, the internal forces and nodal displacement of four schemes under half-span load are similar to those of four schemes under full-span load.

4.2.3 The whole process of the rupture of cables (struts) under external loads

The responses of SCSWIRC with rupture of cables (struts) under full-span load and half-span load have been studied in Section 4.2.1 and Section 4.2.2, but whether the obtained response is the maximum response of SCSWIRC in the whole process of rupture cables (struts), therefore it is also necessary to study the overall mechanical performance of cables and struts in the whole process of rupture cables (struts). In ANSYS software, the transient dynamics module can consider the whole process of rupture cables (struts) by setting the time in the solution stage, and then the time-history post processor can extract the whole response process of rupture cables (struts). Since the maximum internal forces of cables under full-span load is slightly larger than those of components under half-span load, the responses of rupture cables (struts) under full-span load are taken as an example to study the whole response process of SCSWIRC with rupture of cables (struts). Meanwhile, since scheme 2 and scheme 3 are not the optimal grid-jumping layout scheme, the rupture cables (struts) of the original scheme and scheme 1 are only studied and analyzed, and the calculation results are shown in Fig. 11 and Fig. 12.
(a) Maximum internal force of cable when rupturing C1  
(b) Maximum internal force of strut when rupturing C1  
(c) Maximum nodal displacement when rupturing C1  
(d) Maximum internal force of cable when rupturing S1  
(e) Maximum internal force of strut when rupturing S1  
(f) Maximum nodal displacement when rupturing S1  

**Figure 10:** Maximum internal forces of cables and struts and nodal displacements under half-span load F when rupturing C1 and S1

**Table 3:** The response results of four schemes before and after rupture cables (struts) under half-span load

<table>
<thead>
<tr>
<th>Data type</th>
<th>Original scheme</th>
<th>Grid-jumping layout scheme 1</th>
<th>Grid-jumping layout scheme 2</th>
<th>Grid-jumping layout scheme 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No rupture</td>
<td>Rupture</td>
<td>No rupture</td>
<td>Rupture</td>
</tr>
<tr>
<td>Max. internal force of cable (kN)</td>
<td>C5 553.649</td>
<td>C5 598.669</td>
<td>C5 554.171</td>
<td>C5 617.723</td>
</tr>
<tr>
<td>position</td>
<td></td>
<td>Rupture C4</td>
<td>Rupture C5</td>
<td>Rupture C5</td>
</tr>
<tr>
<td>Max. compression internal force (kN)</td>
<td>-40.145</td>
<td>-44.283</td>
<td>-40.043</td>
<td>-44.666</td>
</tr>
<tr>
<td>position</td>
<td>S4</td>
<td>S4</td>
<td>S4</td>
<td>S4</td>
</tr>
<tr>
<td>Max. nodal displacement (m)</td>
<td>-0.413</td>
<td>-0.681</td>
<td>-0.411</td>
<td>-0.674</td>
</tr>
<tr>
<td>position</td>
<td>S4</td>
<td>S4</td>
<td>S4</td>
<td>S4</td>
</tr>
</tbody>
</table>

29
It can be observed from Fig. 11 that the maximum internal force is 859.173 kN and the maximum pressured force is -39.898 kN and the maximum nodal displacement is -0.955 m in the whole process of rupture cables (struts) in the original scheme. It can be observed from Fig. 12 that the maximum internal force is 833.552 kN and the maximum pressured force is -56.901 kN and the maximum nodal displacement is -0.935 m in the whole process of rupture cables (struts) in the scheme 1. The analysis results show that the maximum internal force values of cables and struts of the original scheme and scheme 1 do not exceed the minimum breaking strength of cable of the selected cables and the allowable pressured force of struts. The maximum nodal displacement is -0.955 m, which is still in the acceptable range. Therefore, there is no progressive collapse for original scheme and scheme 1.

**Figure 11:** Time-history curve of the maximum dynamic response of the original scheme with rupture cables (struts)

**Figure 12:** Time-history curve of the maximum dynamic response of the scheme 1 with rupture cables (struts)

5. DISCUSSIONS

The paper studies the rupture cables (struts) of SCWIRC based on transient dynamic theory. The influence laws of self-weight, different prestress levels and grid-jumping layout on the rupture cables (struts) of SCWIRC are obtained. The self-weight has little influence on the SCWIRC with rupture of
cables (struts). The different prestress levels only affect the actual internal force and the variation of internal forces of components does not gradually enlarge with the increase of the feasible prestress levels. The analysis results show that the remaining structure has a better ability to resist the rupture of cables (struts) after the original scheme with grid-jumping layout, which also reveals that the original structure has a better safety reserve function and has a better ability to resist the external loads. The paper studies the structural rupture cables (struts) based on transient dynamic theory. If some scholars are interested in the research contents, LS-DYNA, ABAQUS and the other methods can be used to study the rupture cables (struts) of SCSWIRC. It is also possible to study the rupture of multiple cables and multiple struts. A simple experimental model can be designed to study the rupture of cables (struts) if the funds are sufficient.

6. CONCLUSIONS

Through studying the rupture of cables (struts) of SCSWIRC, the main conclusions are as follows:

(1) Since the average self-weight of per unit area of SCSWIRC is very small, the influence of the self-weight on the SCSWIRC with rupture of cables (struts) is small.

(2) The larger the initial prestress applied to SCSWIRC, the greater the response of the SCSWIRC after rupture of cables (struts). But at the same proportion feasible prestress, the variation of internal forces is basically the same before and after rupture of cables (struts). The same proportion of feasible prestress levels do not amplify the response of SCSWIRC with rupture of cables (struts).

(3) Under the same prestress, the change range of cables’ internal forces and nodal displacements are at the same level for four schemes with the rupture of cables and struts, but the internal forces of struts have changed significantly, which shows that the grid-jumping layout has great influence on the struts of SCSWIRC.

(4) Under full-span load, the responses of four schemes before and after rupture of cables (struts) are basically the same. Although the internal forces of cables and struts and nodal displacements after rupture cables (struts) have changed significantly, the maximum internal forces of cables and struts and the maximum nodal displacements is still in the acceptable range.

(5) Under half-span load, the change laws of internal forces and nodal displacements are basically the same as those of internal forces and nodal displacements under full-span load. Meanwhile, the responses of SCSWIRC under half-span load are slightly larger than that of SCSWIRC under full-span load.

(6) From the time-history analysis results, the maximum internal forces and the maximum nodal displacement are obtained at 2 seconds after rupture cables (struts). However, the maximum internal forces of components in the whole process of rupture cables (struts) does not exceed the allowable value and the maximum nodal displacement is still in the acceptable range, which would not cause the progressive collapse of SCSWIRC.

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REFERENCES:


[25] Liu, R.J., Li, X.Y., Xue, S.D., Marijke M., and Ye J.H., “Numerical and experimental research on annular crossed cable-truss structure under cable rupture”. Earthquake Engineering and

THE IMPACT OF CONTEMPORARY TECHNOLOGY ON SHELL STRUCTURES: MATERIAL AND LIGHT SOLUTIONS

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ABSTRACT

With the development of technology and the materials used, shell structures have developed into more complex forms. This article is a comparison between contemporary and historical shell structures. The change is an effect of the evolution in the design process that is the result of parametric design thinking. The study aims to investigate the impact of new technologies on the architectural form of shell structures. Was there any pivot point in the history of shell structures? The secondary objective of the study is the focus on lighting in such forms and their evolution with the view of the evolution of lighting solutions applied in architecture. With the use of new technologies, shell structures can have a new form and complex detail. They may vary in scale from small objects to large-scale structures.

Keywords: Shell structures, computer design, digital design, sustainable constructions, artificial light, daylight, curvature

1. INTRODUCTION

Shell structures are defined as a rigid thin combination of the carrier and covering system. Hyperbolic paraboloids are surfaces that enable large span widths with small thickness, they are generated by moving in straight lines [1]. The first thin hyperbolic paraboloid concrete shells appeared in France in the 1930s and were created by Bernard Laffaille and Fernand Aimond [2]. In recent years, new technology has significantly increased the diversity in applied constructions [3]. The shell structures from the second half of the XX century were based entirely on reinforced concrete [4]. In the last 20 years, many new materials have been introduced, starting with wooden and steel construction and ending with light composite fibers and elastic textiles. The achieved design form is often a result of material selection [5-6]. The change is also visible in the achieved form. With the development of technology and the materials used, shell structures have developed into more complex forms. The change is an effect of the evolution in the design process that is the result of parametric design thinking [7-8]. In shell structures, the cover element and the carrier element are consistent. Shell structures were used to cover large areas economically and without intermediate support. However, it is also possible to design amorphous shapes in different scales. Besides this, gaps in different shapes and sizes can be made in shell structures with an increasing variety of materials used today and today's technology.

The aim of the study is to investigate the impact of new technologies on the architectural form of shell structures. New technologies are understood as both design and fabrication methods. Among the design methods, it is worth highlighting here the digitization of the design workshop, in particular BIM (Building Information Modeling) technologies or computational design. In the case of fabrication,
technologies related to the automation of creation based on e.g. CNC cutting or the use of robotic tools have an increasing share.

Was there any pivot point in the history of shell structures? If there was, did digital technology have a significant impact? How did the evolution of materials and design methods change the structures and their detail? If the detail is more complex was it connected to the introduction of new materials in shell structures.

The secondary objective of the study is the focus on lighting in such forms and their evolution with the view of the evolution of lighting solutions applied in architecture. What was the character of applied light fixtures? If it has evolved what did new solution led to integration and coherent with the form artificial lighting of the form.

Increasing interest in automation in different fields of engineering has a strong impact on architecture. New design technologies such as scripting automation have a strong impact on the entire discipline. The recent research shows the strong impact of such solutions not only on the design process but also on the final esthetic and character of the design. Architects and designers are exploring new paths and methods of design with increasing interest in numerous forms of automation [9]. Moreover, the architectural education curriculum is developing towards data-based design processes [10] and parametric solutions that increase the flexibility and responsiveness of design [11].

Digital technologies and automation in the design process created the opportunity to improve the quality of detail and application of new forms and materials [12]. Contemporary architectural solutions are often the result of a complex system based on natural patterns of growth [13]. The development of design tools brings a series of new opportunities such as automated creation of floor plans [14] or even entire buildings [15] and, but has to be applied with caution and appropriately selected to meet the needs related to a specific problem. The impact of new technologies on fabrication brought new opportunities to shell structures with the application of materials. The change is visible in the whole field of architectural design [3]. Form finding process is often connected to optimization of the fabrication process that allows for cost management and reduction of manufacturing waste.

The important factor of the change in the design process is driven by the search for more sustainable solutions. The idea is to limit the carbon footprint of design and follow the agenda of three R – reduce reuse recycle [16]. The rising awareness of limited resources and climate change had an impact on all parts of design even applied lighting, to overcome issues such as light pollution[17] The search for more ecological solutions is often the reason for the introduction of emerging technologies into design practice such as block-chain [18]. The recent development of the design process has significantly influenced the way of designing, reducing the consumption of materials and reducing the carbon footprint associated with the operation of buildings.

New technologies are not only positive but also a risk. Automation of the design process may lead to an incomprehensible approach, not only to minor design errors but also to the creation of objects that will not be properly embedded in the urban context. Digitization may also lead to an increase in the repeatability of the constructed objects, but paradoxically it also allows for much greater freedom in the scope of individual adjustment of a repeatable object. However, the greatest risk is the loss of individual design methods and traditional craftsmanship, which often constitute the nature and value of the designed object. A big challenge related to the digitization of a project workshop is the appropriate selection of methods and avoiding repetitive patterns that can reduce the quality of projects.

2. METHODS

The study was conducted in the need for new materials and methods in architectural practice. The method applied in this paper consists of several steps considering historical and contemporary shell structures, development of the design process, new materials applied for shell structures, and new light solutions (Fig. 1). The study is supported by a wide theoretical framework referred to the major direction of change in the discipline of architecture.

The first part of the study focuses on the historical shell structures, with the search for the most relevant ones and their innovation and their future impact on the development of construction and design. The study is supported by an overview of contemporary shell structures with the board view on novelty and reference to historical forms. The outcome of the overview is the selection of elements repeated in a
The selection of examples was preceded by the analysis and comparison of nearly 100 examples of shell structures. The aim of the selection was to find several ones that were most relevant to the development of the design process over nearly 70 years. In the same step, contemporary design methods are analyzed in reference to shell structures, lighting solutions, and newly applied materials are discussed. The outcome of the acquired knowledge of the shell structure is the comprehensive examination of contemporary and historical shell structures with a focus on structural materials. In the same step the evolution of light solutions are discussed and their impact on shell structures. All steps are summarized by the determination of changes in shell structures and an indication of the direction of further development.

3. MATERIALS

The constant evolution of the design method has a strong impact on the final outcome. Architects and designers are searching for new methods and material solutions to create buildings and structures for a variety of reasons from higher quality, and lower cost to a smaller carbon footprint. Nevertheless, development and novelty have been a part of the profession since its very beginning. An example of such are shell structures, the forms that gave architects new means of expression and fewer limits in comparison to traditional reinforced concrete constructions.

The overview of shell structures starts with the pioneering work of Felix Candela who was inspired by the revolutionary thought of Laffaille and Aimond, designed in 1958 shell structure called the Los Manantiales Restaurant [19]. The design of the restaurant at Xochimilco in Mexico was based on a search for a new construction form that could have a large span without any additional construction pillars besides the ones that are on the perimeter of the form. The roof covering the restaurant was formed by an octagonal groined vault. As Tomás and Martí [20] argue: From these early experiences, an enormous variety of vaults with free edges were built: triangular, square, pentagonal, hexagonal, and octagonal. It is created with four intersecting hyperbolic paraboloids. Inside the building, there are eight groins marking the roof surface and affecting the outside appearance of the building [21-22-23]. The interest in hyperbolic paraboloids as Dziewrzynska [24] argues: was caused by its positive static properties, allowing the creation of shells with a large span, as well as a great possibility of various arrangements of single shells in compound ones. It is created out of reinforced concrete, steel, and glass facades that open the building toward the surroundings and let in natural lighting. The formwork system was made by straight stripers, in order to make this shell of a restaurant. When the building is viewed from above, it looks like an 8-leaf flower. As a result of this, daylight is provided from all around. In the interior, the lighting elements can be placed to illuminate equally the entire space of the restaurant. Extensions of hyperbolic paraboloids, which are all over the form, also serve as a fringe and shading element. Candela considers this structure as one of the most important shell structures that he has accomplished. It is unique and it has all of the properties that a shell should have: simple, elegant, and light [21].

Another example of outstanding work of Candela is the Lomas de Cuernavaca Chapel, which was designed in 1958 and built-in 1960, using a single concrete sheet with a hyperbolic paraboloid shape with edges constrained by arches made with traditional formwork. The form of the chapel looks like a saddle and is only 4 cm thick [25-26]. Based on a sketch of a triangular raised roof, Candela reshaped the form into a thin curved structure which made the chapel unique and dramatic [27]. The form expands and rises in the seating area of the chapel which is given a feeling of infinity, it narrows and decreases in the part where the altar is located. The chapel is 30 m wide and reaches 24 m in height [28]. The windows are located on the altar side, and on the other side, the form is completely open. With this form of a hyperbolic paraboloid, daylight was used more and provided the religious structure with a different atmosphere, while offering a unique view of the landscape and mountains of the Cuernavaca Valley.
Since 1951, when Candela designed the Pavilion of Cosmic Rays, he completed several projects that involved shell structures. He experimented with different geometries and spatial solutions. One of his groundbreaking projects was San Vicente de Paul Chapel from 1959 which was designed with Enrique de la Mora and Fernando López Carmona. In the project, he created a dynamic form out of three straight-edged asymmetric hyperbolic paraboloids which were combined with two truss beams. The straight-edged forms have an average thickness of 4 cm achieved with reinforced concrete. The resulting geometries are asymmetrical because of irregular curvature [21-23-28]. The resulting form of a space has a unique character because of the dynamic lines that create the inner form of the building. The shape is opened to the daylight due to the space in between the concrete shapes that were covered with steel and colored glass. Natural lighting was provided by leaving a space between hyperbolic paraboloids, additionally, aesthetic features are provided with the colored glass used.

On the other hand at the time, many other architects and engineers experimented with the new free-form shapes that were introduced to architecture. One of them was Heinz Isler [29-30] who experimented and devoted his work to applying new forms to the discipline. One of his early projects was Wyss Garden Center from 1962, which was created in Solothurn. The Swiss engineer developed new form-finding methods by using expansion, inflation, and hanging of thin membranes. The methods applied by Isler enabled optimal forms in terms of structural behavior. Sasaki [31] defines a membrane shell as an expansion of Antoni Gaudí’s inverted hanging arches to curved surfaces. He balanced perfectly the aesthetics of his shells against their structural efficiency [32-33]. When the dome is viewed from above, it looks like it was cut with four lines from the sides. These openings sides become the facade of the building and are used for lighting and entrance to the building. The structure is constructed on the ground with four points. However, because of the Switzerland climate, it needed additional insulation, as Tang [34] argues: Insulation was used as permanent shuttering in many of Isler’s shells. [...] thin timber boards were placed at regular intervals across the beams or trusses. The insulation was on top of this and has a role as permanent shuttering.

The shell forms were also applied due to the need of a large span. Palazzetto dello Sport was built in Rome, for the Summer Olympic Games in 1960, by Italian architect Annibale Vitellozzi and structural engineer Pier Luigi Nervi. The spherical cap is chosen as the architectural form and there is a pressure circle in the center of the shell. This pressure circle is used for natural lighting and hanging lighting installations. The shell is 58.50 m wide and in height reaches 21 m. To create the cladding of the roof 1620 precast concrete panels were used. With the joining of these panels, radial arcs were formed in the interior of the dome, and this image resembles a sunflower. To reduce the shell thickness by rippling edge stiffening the architect decided to create a ribbed shell dome that was possible due to the use of ferro-cement as a construction material. The material is created out of concrete and rigid steel mesh. The spherical roof is raised from the ground with 36 Y-shaped columns. These Y-shaped columns collected and transferred the forces to the ground [28-33-34].

Newly adopted technologies and materials have a significant impact on the form of contemporary shell structures and their detail. The development of the design process that is the consequence of new tools and materials allowed for new architectural forms and complex detail. However, there is still a strong connection between classical shell structures and new forms that follow the same directions of design.

It is common to base a new design on the principles of the classical one. An attempt like that is the KnitCandela pavilion design by Zaha Hadid Architects and ETH Zurich. It is an exhibition shell structure that pays homage to Candela. The main inspirations for the project were the Los Manantiales Restaurant and the traditional Mexican dress. The textile material was fully automatically knitted [35] at the ETH in Zurich, Switzerland, and then just carried in suitcases to Mexico. At the same time in Mexico City, the supporting structure was built. After mounting the textile material on the form, the construction was insulated to avoid leaks and then covered with concrete. This approach introduces a new kind of formwork that besides taking its basic role can have a visible role in building aesthetics. In the KnitCandela the textile material that was used as formwork for thin concrete shell had a strong impact on aesthetics. A unique colorful inner surface that stands out from other shell structures was created with the custom 3D weft-knitted textile [36-37-38]. Besides, the concept of the supporting frame falsework was to make a self-stressed system that did not require any anchorage into the site ground structure. The structure was designed as a 3 cm-thick
A quite similar design method was used in the Buga Wood Pavilion, which was designed and developed in 2019 by The Institute for Computational Design and Construction (ICD) with the Institute for Building Structures and Structural Design (ITKE) at the University of Stuttgart and BUGA GmbH and Müller Blaustein Holzbauwerke (Daniel Müller, Bernd Schmidt, Oliver Fried, Reinhold Müller). The pavilion was designed using computational design and robotics technologies. The form was inspired by the plate skeleton of sea urchins and is a temporary building with a height of 30 m, built for events and concerts. Each of the 376 polygonal pieces that were created by combining six different wooden layers and joining was done by robots. Wooden parts were screwed together from pre-drilled points. They were installed at the construction site using cranes, in ten working days by a team of two craftsmen [41-42]. Bechert et al. [43] defined segmented shell structures as load-bearing structures composed of individual elements that are joined along their edges. The resulting form is created out of planar elements and is considered a polyhedral plate structure [44-45]. The shell has the function of both carrier and covering element therefore can be classified as a segmented shell structure [45-46]. The empty part of these polygonal elements provides both daylight and space for the design illumination system. In Buga Wood Pavilion, artificial lighting is provided by placing LED light elements in the wooden parts that make up the shell. In addition, the lighting elements placed in each piece illuminated the interior of the shell homogeneously.

The innovative attempt to create a shell structure with assembled multiple elements was made by Marc Fornes from THEVERYMANY. The Hyperbole was composed of flat aluminum parts which we calculated with a computer program. This shell structure consists of 582 3-millimeters thick aluminum panels and is supported by 3 different points on the ground. Compared to the concrete shell structures it is extremely thin. The solution is similar to the use of flat interwoven wood strips, such as in Shigeru Ban projects, which can increase project sustainability [46]. The technology used for the project is a development of technology from early projects of Marc Fornes such as The Labrys Frisae, as Andrew H. Dent and Leslie Sherr [47] argue: only aluminum sheet offers the stiffness, workability, accurate cutting, and permanence that this unique installation possesses. Sometimes, different patterns or color transitions can be seen in structures created by combining pieces such as puzzles. While lighter tones are used in terms of being bright in the interior, these colors may differ on the outside of the building. The color of the structure is light green and gets slightly darker upwards, on the interior near the top is blue, which is reminiscent of a sky and gives a feeling of infinity. Daylight passes through the gaps formed at the joints of these parts and holes created in each panel. Thus, different light games can be seen in the interior depending on the angle of the solar light and the locations of the gaps.

Shadow play and perforation became a permanent part of contemporary shell structures design. Markus Schietsch Architekten in the Kaeng Krachan Elephant Park at Zoo Zurich, have used perforation for the daylighting system. The object is designed for up to ten elephants and has an area of 8,440 square meters [48]. People can closely watch elephants from the glazed pool. Elephants can travel freely between indoors and outdoors. Due to the undulating form of the roof, the height of the edges of the roof
is different from the ground. In parallel with this, since the glass ratios change on the facades, the amount and angle of daylight also changes. There is a reinforced-concrete tension ring at the low point of the roof, which prevents the shell from splaying. The wavy wooden roof was formed from 550 uniquely shaped, cross-laminated spruce panels. The roof has 271 openings providing natural light that sums up to 30 percent of the entire shell, and at the same time, the weight of the shell is reduced [49-50-51]. Natural light coming from the roof is highly important for inhabitants and necessary for elephant vegetation. The necessity is emphasized by Maulana [52]: The conditions are even if the elephants are not free, trying to create a home for elephants to feel in their natural environment.

4. RESULTS

Nowadays shell structures are based on the heritage of pioneering achievements of technology from the mid-twentieth century. Los Manantiales Restaurant, Chapel of Vincent, Lomas de Cuernavaca Chapel, KnitCandela, Hyperbole, Trifolium are based on a geometric form of a hyperbolic paraboloid. Wyss Garden Center, Palazzetto dello Sport, Buga Wood Pavilion, and Kaeng Krachan Elephant Park are created in the form of a dome(Figure 2). The differences between objects are visible in materials used for the construction and approach towards the usage of daylight. Even though the general idea and the shape are similar there are a lot of significant differences in the achieved form and process of construction. New material applied in shell structures allowed the creation of even thinner and lighter construction with more openings (Figure 5).

New technologies such as parametric design, scripting, or automation allow for more precise construction and material selection freedom. With the change in architectural design that incorporates more often the process of fabrication that change is visible in the material selection that spread from wood through steel and aluminum event to textile(Figure 3). Early shell structures were made almost entirely out of the cast-in-place reinforced concrete while contemporary objects use cutting-edge technology such as double-curvature self-supporting form created with planar aluminum plates, through textile-material formwork, wooden panels to robotically cut Corian heat-bent panels. The change is a result of the 1990s digital technologies revolution [3-53] that has significantly changed the process of design [50] and had a huge impact on the resulting forms. As noticed by Šimkovič et al: The digital approach to architecture - algorithmic, parametric, emergent modelling processes - have the ability to process complex influences and reflect them in the formal and/or programmatic structure of architecture and design [54].

Figure 2: Shell structures development
designed structures in relation to objects traditionally made of reinforced concrete.

Figure 3: Structural materials in shell structures

Figure 4: Light solutions in shell structures

The scope of analysis related to lighting is very wide. Light can be analyzed in terms of daylight - atmospheric light, as well as artificial light and its integration into the form of a building. Each of the above can be considered on the basis of its parameters, color, or strength, but also the climate that gives the object or, for example, the way in which it changes the architectural expression of the object. The conducted analyzes, however, focus on the basic aspects related directly to the form of the object, i.e. the type of artificial lighting used and the method of using daylight. The changes that have taken place in the design methods and materials used have had a significant impact on both of the above aspects.

Moreover, the way of lighting the interior has changed due to recently introduced materials in shell structures. In the early projects, the light was let in through the glazing located between the individual forms, today architects are eager to use the holes in the construction material itself, which gives more freedom in the form-finding process and enables even interior lighting with daylight (Figure 4).

However, there were expectations from this such as Candela’s Textile Factory from 1954 or Isler’s Coop Warehouse from 1960, where lightning was created with regular perforation [54]. However, such a solution was a minority back at the time. Direct access to daylight is beneficial for health and should be considered one of the most important factors in the design process [55]. The development of the lighting system also contributes to energy savings [56]. In some recent examples such as the Buga Wood Pavillion or the Kaeng Krachan Elephant Park, artificial illumination systems became fully integrated into the form, so that the illumination naturally highlights the designed form of the object.

Figure 5: Change in shell structures – increased complexity of form and importance of detail

5. DISCUSSION

Shell structures are one of the most efficient and material-saving solutions for large-span objects. This ongoing change is also affected but new materials such as wood and bamboo [57]. The material solution can also decrease the carbon footprint of the designed building. The scope of materials used in the design process should be extended with the analysis of alternative material solutions and the importance of design decisions within the context of sustainable design should be emphasized. It is also relevant to notice the detail of form and its impact on the final quality of the achieved architectural form (Figure 5). This does not mean that the creators following the traditional workshop did not pay attention to the details of the project, but that the possibilities of refining and analyzing them were smaller. Moreover, the multitude of materials currently used in shell structures means that we are often dealing with very unusual solutions related to their joining. A perfect example of this is the proprietary fabrication method used by THEVERYMANY, based on the parallel joining of thin aluminum panels of various colors.
with rivets. It can change the interior exposure to the daylight and allow for better suited to the form and highlighting its characteristic features. Moreover, the size of structures and distances between construction elements has increased. Today, it is possible to design free-form, functional, effective shell structures by using shell geometries whose curvature is determined by the architect.

Moreover, it can also impact access to daylight and provide opportunities for designing integrated lighting systems that have a lesser impact on the natural environment [58]. The proper selection of lighting system can also emphasize the final architectural form and make its spatial components visible[59]. It can also increase comfort and living qualities inside the building [60]. The use of light in built environments has comfort, behavioral, economic, and environmental consequences [61]. The correct design illumination can have an impact on economic factors such as the need to replace plants or the quality of life for humans[62]. Reinforced concrete shells with large spans often lack daylight, for this reason, it is important to have additional gaps for lighting, however, created in a way to limit the effect on the static of the shell structure [63]. In order to allow light to reach the required amount proportionally, lighting can also be provided from the top by designing galleries, skylights, or pressure rings in the domes. Also, if there are gaps in the side parts due to the form of the structure, these can provide natural lighting. Sometimes the shell structure may consist of a combination of several minor shell structures. Gaps that are left between these shells may provide natural lighting and ventilation. Elevating the dome from the ground with columns changes the angle of incidence of sun rays, as a result, the amount and intensity of daylight are increased [64].

The differences related to the achieved form, the type of material used, and the method of illumination of the object with daylight and artificial light were analyzed. However, it should be noted that due to the introduction of a number of changes in both the design and construction process, other features have changed, such as structural behavior, solutions that allow for obtaining appropriate stiffness, ways of relieving the structure or methods of providing insulation in terms of obtaining required humidity and temperature. The above may be a good starting point for further considerations.

6. CONCLUSIONS

The architectural design process through the years has developed and incorporated many new aspects such as digital fabrication, parametric design, scripting, and even automation. The development has been supported by the rising awareness of environmental challenges. All that has a major impact on created forms, used materials, types of lighting, and architectural detail. Due to the pioneering character of shell structures, the change we can observe is even more visible than in other architectural objects.

Nowadays, different materials are being used for creating shell structures. Constructions are based on traditional reinforced concrete created on wooden formwork or on emerging new solutions such as textile supporting structures. Moreover, steel, textile, and wood have been used for creating shell structures. These materials can be used separately or in a combination. For example, wooden parts can be joined with fiber or yarn. New materials and technologies led to different more precise detail-oriented designs and new possibilities for illuminating with daylight and artificial light systems. With the use of new technologies, shell structures can lead to many different forms. They may vary in scale from small objects to large-scale structures. These merged processes can involve advanced robotics to reduce tolerance and create structures more precisely. Moreover, with the rising cost of human labor, robots can soon become a permanent solution for more complex constructions.

REFERENCES


INFLUENCE OF CENTER-HUNG SCOREBOARD ON SEISMIC RESPONSE OF SINGLE-LAYER SPHERICAL RETICULATED SHELL UNDER ONE-DIMENSIONAL HORIZONTAL EARTHQUAKE

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ABSTRACT

The center-hung scoreboard is large-scale display device flexibly suspended in the center of the gymnasium. The influence of center-hung scoreboard on seismic response of single-layer spherical reticulated shell is not clear. In this paper, the FEA models of coupling systems composed of single-layer spherical reticulated shell and center-hung scoreboard are established. The seismic responses of coupling systems are calculated by explicit dynamic time history method. The seismic responses of the coupling systems are compared between the flexibly suspended case and the simplified case where the scoreboard is simplified as fixed mass of the support platform. The effects of the sling length and the scoreboard weight on seismic responses of the coupling systems are also discussed. Compared with the simplified case, peak values of displacements, accelerations and axial force are significantly different when the scoreboard is flexibly suspended. The treatment method of simplifying the scoreboard as fixed mass of the support platform is dangerous. The sling length and the scoreboard weight have significant effects on peak values of displacements, accelerations and axial forces of the coupling systems. The envelope values under different sling lengths and different weight should be taken as seismic response results for structural design.

Keywords: Single-layer spherical reticulated shell, Seismic response, Center-hung scoreboard, Scoreboard weight, Sling length

1. INTRODUCTION

Single-layer reticulated shell structure is widely used in construction engineering due to its reasonable bearing capacity, various shapes and large span. Many large-scale public facilities adopt single-layer reticulated shells. Many cities in the world are located in earthquake affected areas. Single-layer reticulated shell structure is a typical long-span spatial structure, which has the characteristics of dense frequency, complex vibration mode and complex seismic responses [1].

Research on seismic responses of single-layer reticulated shells has been done and obtained many achievements. Fan et al. [2] took the K8 single-layer spherical reticulated shell as an example to analyze the seismic response, found that the traveling effect of ground motion, roof weight, rise to span ratio and member sections have a non-negligible influence on the seismic responses. Zhong et al. [3] found that single-layer reticulated shells with large rise to span ratio or large roof weight are more likely to be damaged in earthquake. Cedrón et al. [4] clarified the influence of horizontal seismic component and vertical seismic component on the nonlinear seismic response of internal force of cylindrical reticulated shell. Nie et al. [5] discussed the seismic damage and possible damage causes of spatial double-layer grid...
structure in Lushan earthquake, and summarized the possible damage causes. Yang et al. [6] used the multi-segment beam method to simulate the initial defects of members, found that initial defects have non-negligible impact on the seismic responses of the single-layer reticulated shell. Fan et al. [7] studied the stability of single-layer reticulated shell with initial curvature of structural members, found that initial curvature of structural members significantly reduces the buckling load of the structure, change the buckling mode and plastic development of the structure. Li et al. [8] also pointed out that under severe earthquake, effects of geometric nonlinearity and material nonlinearity should be considered. Zhang et al. [9] conducted study on seismic damage of single-layer reticulated shell under far-field and near-field seismic action, found that the near-field ground motion causes greater dynamic response and seismic damage than far-field ground motion. Yu et al. [10] conducted incremental dynamic analysis on aluminum alloy cylindrical reticulated shells with different structural parameters, and obtained the vulnerability curve that can be used to predict the failure probability under different seismic levels. Chen et al. [11] and Kong et al. [12] respectively studied the influence of vertical variable stiffness isolation bearing and FPB bearing on the seismic response of single-layer reticulated shell. Li et al. [13] conducted study on the anti-seismic performance of cable-reinforced single-layer reticulated shell, found that the cable stiffening system can greatly improve the anti-seismic performance. Wang et al. [14] discussed the local optimal solution of shape optimization of cable stiffened reticulated shells and proposed an improved optimization method. Zhao et al. [15] pointed out that in practical engineering, the response spectrum formula should consider the effects of multi-dimensional, traveling effects and the coupling of dynamic and quasi-static forces. Nie et al. [16] found that there are two possible failure forms of single-layer reticulated shells under severe earthquakes, dynamic instability and strength failure. Yan et al. [17] proposed a method to identify key components in single-layer reticulated shell, and confirmed the progressive collapse mechanism. In summary, the current seismic response analysis methods of single-layer reticulated shells include the mode decomposition response spectrum method, the dynamic time history method, incremental dynamic analysis method, static pushover method and two-stage pushover analysis method [18]. The rise span ratio, the initial defects of members, the supporting forms of reticulated shells and the multi-dimensional seismic action and traveling effects of seismic waves should not be ignored in seismic response analysis.

The center-hung scoreboard is a kind of large display equipment flexibly suspended in the center of the gymnasium [19-20]. With the development of professional sports and commercial entertainments, the number of center-hung scoreboards has increased rapidly in recent years. In order to pursue better display performance, the center-hung scoreboards are developing in the trend of large display areas and small pixel spacing. In results, the weight of the center-hung scoreboards increases significantly [19], forming a large suspension mass in the center of the roof. Liu et al. [21] analyzed the influence of center-hung scoreboard on the vibration characteristics of single-layer reticulated shell, found that influence of the flexibly suspended center-hung scoreboard on the natural vibration characteristics cannot be ignored, especially on the low-order frequency and vibration mode. There are significant differences in vibration characteristics between the center-hung scoreboard and the roof structure, which will inevitably produce interaction under earthquakes. At present, there are few studies on the interaction between the two under earthquakes, and the influence of the center-hung scoreboard on the seismic responses of single-layer reticulated shell needs to be further revealed. It’s not clear that the treatment method of simplifying the center-hung scoreboard as fixed mass on roof structure is safe. Since the scoreboard weight and the sling length determine the vibration characteristics of the center-hung scoreboard, parametric analysis should be done to found the influence effect of the two factors.

This paper aims to explore the influence of the weight and the sling length of center-hung scoreboard on seismic response of single-layer spherical reticulated shell. The FEA models of coupling systems composed of flexibly suspended center-hung scoreboard and single-layer spherical reticulated shell are established, and seismic responses of coupling systems are analyzed by explicit dynamic time history method. The responses of coupling systems are compared between the flexibly suspended scoreboard and the simplified case where the scoreboard is simplified as the fixed mass on the support platform. The effects of the sling length and the scoreboard weight on seismic responses of coupling systems are studied. The research results of this paper have reference value for the design and analysis of single-layer reticulated shell with center-hung scoreboard.
2. MODEL AND ANALYSIS METHOD

2.1. FEA model

Figure 1: Schematic diagram of the coupling system: (a) front view, (b) Support platform, (c) Plan of the shell

Taking the single-layer spherical K6 reticulated shell as an example, the diameter of the shell is 60 m, the rise to span is 1/6, and the boundary condition is assumed to be three-way fixed hinge bearing support. The center of the reticulated shell is provided with a center-hung scoreboard and a support platform for the scoreboard, as shown in Figure 1(a). The support platform and the single-layer spherical reticulated shell are connected by circular steel pipes. The center-hung scoreboard and the support platform are connected by slings. Q355B and circular pipe sections are used for reticulated shell members and vertical members of the support platform, shown as Figure 1(b). Q355B and hot-rolled H-sections are used for horizontal members of the support platform. The elastic modulus of Q355B steel is 206 GPa and the yield strength is 355 MPa. Galvan-coated spiral cables are used for the slings. The tensile strength of the cable is 1670 MPa and the elastic modulus is taken as 160 GPa.

The section specifications for structural members are list in Table 1. The location of different section numbers is shown in Figure 1(b) and 1(c). The length of sling and the weight of scoreboard are the main parameters affecting dynamic characteristics of the scoreboard. Hence, the effects of the two factors on the seismic response of coupling systems are mainly concerned. Sling length is taken every 0.5 m between 0 m and 9 m. The case of 0 m means that the scoreboard is simplified as fixed mass of the support platform. In recent years, the number of center-hung scoreboards with weight of more than 20 t has increased significantly. The heaviest center-hung scoreboard has reached 50 t. The weight of scoreboards is taken every 5 t between 20 t and 60 t. The characteristic value of uniformly distributed roof dead load ($D$) is 1.0 kN/m², the characteristic value of uniformly distributed roof live load ($L$) is 0.5 kN/m². The representative value of gravity load is $1.0 \times D + 0.5 \times L$.

<table>
<thead>
<tr>
<th>Section number</th>
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<th>Materials</th>
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<td>Q355B</td>
</tr>
<tr>
<td>G2</td>
<td>φ273×14</td>
<td></td>
</tr>
<tr>
<td>G3</td>
<td>φ245×14</td>
<td></td>
</tr>
<tr>
<td>G4</td>
<td>φ245×12</td>
<td></td>
</tr>
<tr>
<td>G5</td>
<td>φ230×12</td>
<td></td>
</tr>
<tr>
<td>G6</td>
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<td>φ245×10</td>
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</tr>
<tr>
<td>G11</td>
<td>HN550×200</td>
<td>Galvan-coated spiral cable</td>
</tr>
<tr>
<td>S1</td>
<td>φ12</td>
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</table>

2.2. Analysis method

The dynamic explicit time history method can consider the elastic and elastic-plastic properties of the structural members, and can analyze the dynamic response of the mechanism system [21-22]. It has strong applicability in considering the seismic response analysis of the single-layer spherical
The motion equation of the structural system can be established by D’Alembert principle, and Hamilton principle. The differential equation of elastic motion of the multi-degree of freedom structural system under earthquakes is expressed as EQ. (1).

\[
\]

(1)

Where \([M]\), \([C]\), \([K]\) are the mass matrix, damping matrix and stiffness matrix of the structure respectively, and \(u''\), \(u'\), \(u\) are the node displacement array, node velocity array and node acceleration array respectively, which \(u''(t)\) are the ground motion acceleration array.

When the structure enters the plastic state, the damping matrix \([C]\) and overall stiffness matrix \([K]\) of the structure will change with time. Therefore, EQ. (1) is changed to the form of incremental equation. The differential equation of elastic-plastic motion of multi-degree of freedom structural system under earthquakes is as EQ. (2).

\[
\]

(2)

Of which,

\[
\{\Delta u''\} = u''(t + \Delta t) - u''(t)
\]

(3)

\[
\{\Delta u'\} = u'(t + \Delta t) - u'(t)
\]

(4)

\[
\{\Delta u\} = u(t + \Delta t) - u(t)
\]

(5)

The common integration methods are: central difference method, linear acceleration method, Newmark-\(\beta\) method and Wilson-\(\theta\) method, etc. The explicit dynamic method used in this paper is the central difference method. The central difference method is based on finite difference approximation of the displacement time derivative. If equal time step \(\Delta t = \Delta t\) is selected, the central difference expression of velocity and acceleration at time \(t\) is expressed as EQ. (6).

\[
u'' = \frac{u_{i+1} - u_{i-1}}{2\Delta t}, \quad u'' = \frac{u_{i+1} - 2u_i + u_{i-1}}{(\Delta t)^2}
\]

(6)

The equation of motion of the structural system is EQ. (7).

\[
u''(t) + cu'(t) + ku(t) = P(t)
\]

(7)

By substitute equation (6) into equation (7), EQ. (8) is obtained.

\[
m\frac{u_{i+1} - 2u_i + u_{i-1}}{(\Delta t)^2} + c\frac{u_{i+1} - u_{i-1}}{2\Delta t} + ku_i = P_i
\]

(8)

In EQ. (8), \(u_i\) and \(u_{i-1}\) are assumed to be known, that is, the structural motion at time \(t_i\) and before is a known quantity, and the known term can be obtained by moving the term to the right of the equation:

\[
\frac{m}{(\Delta t)^2}u_{i+1} - \frac{2m}{(\Delta t)^2}u_i + \frac{c}{2\Delta t}u_{i-1} = P_i - \frac{m}{(\Delta t)^2}u_i - \frac{c}{2\Delta t}u_{i-1}
\]

(9)

To sum up, the structural dynamic response at time \(t_i\) can be obtained from EQ. (9). In the multi-degree of freedom structural system, \(m\), \(c\) and \(k\) in EQ. (9) can be replaced by \([M]\), \([C]\) and \([K]\).

2.3. Seismic wave selection

According to GB 50011-2010 (2016 Edition) [23], when time history method is adopted, actual earthquake records and artificial simulated time histories are selected according to the classification of construction site and design earthquake. The number of actual earthquake records should not be less than 2/3 of the total. The average seismic influence coefficient curve of multiple groups of time histories should be statistically consistent with the seismic influence coefficient curve adopted by the mode decomposition response spectrum method. When three groups of acceleration time history curves are used, the envelope values are taken as the calculation results.

When selecting seismic waves, three elements of ground motion should be fully considered, ground motion intensity, ground motion spectrum characteristics and ground motion duration. The ground motion intensity is generally the peak acceleration. Amplitude modulation is carried out according to the peak acceleration corresponding to the fortification intensity, and the peak acceleration is adjusted according to EQ. (10). The selected seismic waves are amplitude modulated according to the peak acceleration of 8 degrees rare earthquake with the design basic acceleration of 0.3 g, and the maximum horizontal acceleration after amplitude modulation is 510 cm/s².
\[ a_0(t) = \frac{a_{0,\text{max}}}{a_{\text{max}}} a(t) \]  

(10)

Where \( a_0(t) \) and \( a_{0,\text{max}} \) are the adjusted seismic acceleration curve and peak value. \( a(t) \) and \( a_{\text{max}} \) are the original recorded seismic acceleration curve and peak value.

Considering the spectrum characteristics of ground motion, the dominant period of the selected seismic waves should be consistent with the design characteristic period, and the epicentral distance of the selected seismic waves shall be consistent with that of the proposed site. In this paper, class II site is adopted, the design earthquake is divided into the second group. Two natural seismic records including El-Centro wave, Taft wave, and one artificial time history RH4TG040 are selected.

The determination principles of ground motion duration are as follows. 1) The strongest part of seismic record shall be included in the selected duration. 2) When the elastic maximum seismic response analysis is carried out for the structure, the duration can be shorter, and when the elastic-plastic maximum seismic response analysis or energy dissipation process analysis is carried out for the structure, the duration can be longer. 3) Generally, it can be 5 ~ 10 times of the basic period of the structure. The adjusted acceleration time history curves in the main direction of seismic waves are shown in Figure 2 to Figure 4, respectively. The seismic wave response spectrum curves, design response spectrum curve and average response spectrum curve of selected seismic waves after amplitude modulation are shown in Figure 5. It shows that the selected waves are well consistent with the design response spectrum curve.

2.4. Seismic wave input direction

When the seismic fortification intensity is 8 degrees, the horizontal seismic analysis shall be carried out for spatial grid structures such as single-layer reticulated shells [24]. In this paper, the one-dimensional horizontal earthquake is mainly considered. Multi-point consistent input method is used for seismic wave input. The horizontal seismic waves are input parallel to the x-axis direction from all the supports, respectively. Due to the limitation of pages, the multi-dimensional effect and the traveling effect of the earthquake remain to be studied in the future.
3. RESULTS AND ANALYSIS

3.1. Influence of center-hung scoreboard on the node acceleration

According to GB 50011-2010 (2016 Edition), the envelope value of the seismic responses under the three groups of seismic waves is taken as the resultant response. The $a_{i_{\text{max}}}^{(w)}$ represents the peak acceleration of the node number $i$ in the structure, the scoreboard weight is $w$ and the sling length is $l$. Then symbol $\rho_{i_{\text{max}}}^{w,l}$ is the peak change rate of nodal acceleration of node number $i$ and it is obtained according to Eq. (11), where $a_{i_{\text{max}}}^{(w,0)}$ represents the peak acceleration of the node number $i$ when the scoreboard is simplified as fixed mass on the support platform and the weight is $w$. By analysis on $\rho_{i_{\text{max}}}^{w,l}$, the influence of weight and sling length of the center-hung scoreboard on the peak acceleration can be revealed.

$$\rho_{i_{\text{max}}}^{w,l} = \frac{a_{i_{\text{max}}}^{(w,l)} - a_{i_{\text{max}}}^{(w,0)}}{a_{i_{\text{max}}}^{(w,0)}}$$  \hspace{1cm} (11)

According to Eq. (12) and Eq. (13), the maximum value $\rho_{\text{max}}^{w,l}$ and minimum value $\rho_{\text{min}}^{w,l}$ of the peak change rate of nodal acceleration in the whole structure can be calculated, respectively. By the analysis, the overall impact of scoreboard weight and sling length on the peak acceleration of all nodes can be discussed. In Eq. (12) and Eq. (13), $n$ represents the total number of nodes. Since $\rho_{\text{max}}^{w,l}$ and $\rho_{\text{min}}^{w,l}$ of the reticulated shell are quite different from those of the support platform, the reticulated shell and the support platform will be discussed separately.

$$\rho_{\text{max}}^{w,l} = \max\{\rho_{1_{\text{max}}}^{w,l}, \rho_{2_{\text{max}}}^{w,l}, \rho_{3_{\text{max}}}^{w,l}, \rho_{\text{n}_{\text{max}}}^{w,l}, \rho_{\text{n}_{\text{max}}}^{w,l}\}$$  \hspace{1cm} (12)

$$\rho_{\text{min}}^{w,l} = \min\{\rho_{1_{\text{max}}}^{w,l}, \rho_{2_{\text{max}}}^{w,l}, \rho_{3_{\text{max}}}^{w,l}, \rho_{\text{n}_{\text{max}}}^{w,l}, \rho_{\text{n}_{\text{max}}}^{w,l}\}$$  \hspace{1cm} (13)

Figure 6 and Figure 7 show the contour diagrams of $\rho_{\text{max}}^{w,l}$ and $\rho_{\text{min}}^{w,l}$ of the reticulated shell varying with sling length and scoreboard weight. Figure 8 and Figure 9 show the contour diagrams of $\rho_{\text{max}}^{w,l}$ and $\rho_{\text{min}}^{w,l}$ of the support platform varying with sling length and scoreboard weight.

Figure 6 shows that $\rho_{\text{max}}^{w,l}$ of the reticulated shell nodes is between 47.1% and 64.5%. The maximum value occurs when the scoreboard is 40 t and the sling length is 1 m. When the scoreboard is between 35 t and 45 t, $\rho_{\text{max}}^{w,l}$ is not significantly affected by the change of scoreboard weight and sling length, and $\rho_{\text{max}}^{w,l}$ remains above 60%. When the scoreboard is away from 40 t, $\rho_{\text{max}}^{w,l}$ decreases significantly. When the scoreboard is 60 t and the sling length is 9 m, $\rho_{\text{max}}^{w,l}$ is the smallest, which is 47.1%. Overall, the sling length has little effect on $\rho_{\text{max}}^{w,l}$ of the reticulated shell, and $\rho_{\text{max}}^{w,l}$ decreases slowly with the increase of the sling length. The scoreboard weight has a significant impact on $\rho_{\text{max}}^{w,l}$ of reticulated shell nodes. With the increase of the scoreboard weight, $\rho_{\text{max}}^{w,l}$ increases first and then decreases.

Figure 7 shows that $\rho_{\text{min}}^{w,l}$ values of reticulated shell nodes are between -39.4% and -19.5%. The minimum $\rho_{\text{min}}^{w,l}$ occurs when the scoreboard is 40 t and the sling length is 9 m, and the maximum $\rho_{\text{min}}^{w,l}$
occurs when the scoreboard weight is about 60 t and the sling length is 1 m. When the scoreboard weight is within 35 t and 45 t, $\rho_{\text{min}}^{w/l}$ values of reticulated shell nodes are less than -28%, which is maintained at a low level. With the weight away from 40 t, $\rho_{\text{min}}^{w/l}$ values generally tend to rise. Figure 7 shows that when the sling length is between 4.5 m and 5.5 m, $\rho_{\text{min}}^{w/l}$ values basically do not change. When the sling length is less than 4.5 m or greater than 5.5 m, weight and sling length affect the $\rho_{\text{min}}^{w/l}$ values at the same time, but the law is complex.

Figure 8 shows that $\rho_{\text{max}}^{w/l}$ values of the support platform nodes are between -37% and 257%, and the maximum $\rho_{\text{max}}^{w/l}$ occurs when the scoreboard weight is 60 t and the sling length is 4 m. When the weight is 60 t and the sling length is greater than 3 m, $\rho_{\text{max}}^{w/l}$ values are not affected by sling length, and $\rho_{\text{max}}^{w/l}$ values remain above 240%. Along with the decrease of scoreboard weight, $\rho_{\text{max}}^{w/l}$ values decrease significantly from positive to negative. When the weight is 20 t and the sling length is 1 m, the $\rho_{\text{max}}^{w/l}$ value is the smallest, as low as -37%. The negative value of $\rho_{\text{max}}^{w/l}$ means that the peak acceleration of all nodes on the support platform is lower than that of the simplified case. Overall, the sling length has little effect on $\rho_{\text{max}}^{w/l}$ values of support platform nodes. The scoreboard weight has a significant impact on $\rho_{\text{max}}^{w/l}$ values of support platform nodes. With the increase of scoreboard weight, $\rho_{\text{max}}^{w/l}$ values increase significantly.

Figure 9 shows that $\rho_{\text{min}}^{w/l}$ values of support platform nodes are between -43.5% and 57%. The maximum $\rho_{\text{min}}^{w/l}$ occurs when the scoreboard is 50 t and the sling length is 1 m. The minimum $\rho_{\text{min}}^{w/l}$ occurs when the scoreboard weight is 20 t and the sling length is 1 m. A positive value of $\rho_{\text{min}}^{w/l}$ means that the peak acceleration of all nodes on the support platform is higher than that of the simplified case. When the scoreboard is within 50 t and 60 t and the sling length is between 3 m and 6 m, $\rho_{\text{min}}^{w/l}$ values are not significantly affected by scoreboard weight and sling length, and $\rho_{\text{min}}^{w/l}$ value remains above 30%. When the scoreboard weight is less than 50 t, $\rho_{\text{min}}^{w/l}$ values increase first and then decrease slowly with the increase of sling length. The $\rho_{\text{min}}^{w/l}$ values reach local peak when the scoreboard is 30 t and the sling length is 5 m.
and the peak acceleration of the nodes in the central part of the reticulated shell is smaller than that of the simplified case. Further, $\rho_{j,\text{max}}^{w,l}$ values of the nodes near reticulated shell supports and close to the Y-axis is about 0. For support platform nodes, the influence law of scoreboard weight and sling length on the peak acceleration change rate of different nodes is complex. It is observed that when scoreboard weight is between 50 t and 60 t, $\rho_{j,\text{max}}^{w,l}$ values are more than 79.1%, and the maximum value is 256.7%, which is significantly higher than that when the scoreboard weight is small. On the whole, $\rho_{j,\text{max}}^{w,l}$ values of scoreboard suspension nodes are greater than those of other nodes on support platform.

To sum up, compared with the simplified case, the peak acceleration of nodes in the case where the scoreboard is flexibly suspended is significantly different, in terms of both values and spatial distribution. The change of peak acceleration of nodes caused by the change of scoreboard weight and sling length cannot be ignored. Compared with the simplified case, the peak acceleration of the nodes near the reticulated shell supports is larger and the peak acceleration of the nodes in the center of the reticulated shell is smaller in the case of flexible suspension. $\rho_{j,\text{max}}^{w,l}$ values of scoreboard suspension nodes are significantly greater than those of other nodes on the support platform.

3.2. Influence of center-hung scoreboard on the axial force

$F_{j,\text{max}}^{w,l}$ represents the peak axial force of the $j$th structural member when the scoreboard weight is $w$ and the sling length is $l$. Then, according to EQ. (14), the change rate $\gamma_{j,\text{max}}^{w,l}$ of peak axial force of the $j$th structural member can be obtained. $F_{j,\text{max}}^{w,0}$ is the peak axial force of the $j$th member when the scoreboard is simplified and the scoreboard weight is $w$. By the analysis on $\gamma_{j,\text{max}}^{w,l}$, the influence law of scoreboard weight and sling length on the peak axial force of structural members can be obtained.

$$\gamma_{j,\text{max}}^{w,l} = \frac{F_{j,\text{max}}^{w,l} - F_{j,\text{max}}^{w,0}}{F_{j,\text{max}}^{w,0}}$$  \hspace{1cm} (14)

According to EQ. (15) and EQ. (16), the maximum $\gamma_{\text{max}}^{w,l}$ and the minimum $\gamma_{\text{min}}^{w,l}$ of axial force in the whole structure can be calculated, respectively, so as to analyze the overall impact of scoreboard weight and sling length. In EQ. (15) and EQ. (16), $P$ represents the total number of structural members.

$$\gamma_{\text{max}}^{w,l} = \max \{\gamma_{1,\text{max}}^{w,l}, \gamma_{2,\text{max}}^{w,l}, \gamma_{3,\text{max}}^{w,l}, \gamma_{P,\text{max}}^{w,l}\}$$  \hspace{1cm} (15)

$$\gamma_{\text{min}}^{w,l} = \min \{\gamma_{1,\text{max}}^{w,l}, \gamma_{2,\text{max}}^{w,l}, \gamma_{3,\text{max}}^{w,l}, \gamma_{P,\text{max}}^{w,l}\}$$  \hspace{1cm} (16)

Since $\gamma_{\text{max}}^{w,l}$ and $\gamma_{\text{min}}^{w,l}$ of reticulated shell members and those of supporting platform members are quite different, they will be discussed separately. Figure 10 and Figure 11 show contour diagrams of $\gamma_{\text{max}}^{w,l}$ and $\gamma_{\text{min}}^{w,l}$ of reticulated shell members varying with sling length and scoreboard weight, respectively. Figure 12 and Figure 13 show contour diagrams of $\gamma_{\text{max}}^{w,l}$ and $\gamma_{\text{min}}^{w,l}$ of support platform members varying with sling length and scoreboard weight, respectively.

Figure 10 shows that $\gamma_{\text{max}}^{w,l}$ values are between 33.5% and 556%, and the maximum value occurs when the scoreboard is 60 t and the sling length is 2 m. When the sling length is less than 4 m, $\gamma_{\text{max}}^{w,l}$ first decreases significantly and then increases slightly with the decrease of scoreboard weight. When the scoreboard is between 60 t and 45 t, $\gamma_{\text{max}}^{w,l}$ value decreases rapidly, and when the scoreboard is between 35 t and 20 t, $\gamma_{\text{max}}^{w,l}$ increases slowly. When the sling length exceeds 4 m, $\gamma_{\text{max}}^{w,l}$ value is not affected by scoreboard weight and sling length, and $\gamma_{\text{max}}^{w,l}$ remains below 180%. When the scoreboard is between 35 t and 45 t, $\gamma_{\text{max}}^{w,l}$ value basically does not change with the sling length.

![Figure 10: Contour diagram of $\gamma_{\text{max}}^{w,l}$ values of reticulated shell members](image-url)
Table 2: Contour diagrams of peak acceleration change rate of the reticulated shell and supporting platform

<table>
<thead>
<tr>
<th>Weight Length</th>
<th>20 t</th>
<th>30 t</th>
<th>40 t</th>
<th>50 t</th>
<th>60 t</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 m</td>
<td>$\rho_{\text{min}}^{1} = -36.4%$, $\rho_{\text{max}}^{1} = -43.2%$</td>
<td>$\rho_{\text{min}}^{1} = -10.0%$, $\rho_{\text{max}}^{1} = -15.3%$</td>
<td>$\rho_{\text{min}}^{1} = -19.7%$, $\rho_{\text{max}}^{1} = -2.40%$</td>
<td>$\rho_{\text{min}}^{1} = -110.1%$, $\rho_{\text{max}}^{1} = -56.6%$</td>
<td>$\rho_{\text{min}}^{1} = -132.9%$, $\rho_{\text{max}}^{1} = -7.70%$</td>
</tr>
<tr>
<td>2 m</td>
<td>$\rho_{\text{min}}^{2} = -3.50%$, $\rho_{\text{max}}^{2} = -19.1%$</td>
<td>$\rho_{\text{min}}^{2} = -7.80%$, $\rho_{\text{max}}^{2} = -8.50%$</td>
<td>$\rho_{\text{min}}^{2} = -3.60%$, $\rho_{\text{max}}^{2} = -2.50%$</td>
<td>$\rho_{\text{min}}^{2} = -92.6%$, $\rho_{\text{max}}^{2} = -40.4%$</td>
<td>$\rho_{\text{min}}^{2} = -186.9%$, $\rho_{\text{max}}^{2} = -0.00%$</td>
</tr>
<tr>
<td>4 m</td>
<td>$\rho_{\text{min}}^{4} = -9.60%$, $\rho_{\text{max}}^{4} = -28.5%$</td>
<td>$\rho_{\text{min}}^{4} = -58.7%$, $\rho_{\text{max}}^{4} = -29.6%$</td>
<td>$\rho_{\text{min}}^{4} = -18.8%$, $\rho_{\text{max}}^{4} = -12.6%$</td>
<td>$\rho_{\text{min}}^{4} = -101.2%$, $\rho_{\text{max}}^{4} = -51.2%$</td>
<td>$\rho_{\text{min}}^{4} = -256.8%$, $\rho_{\text{max}}^{4} = -44.3%$</td>
</tr>
<tr>
<td>5 m</td>
<td>$\rho_{\text{min}}^{5} = -55.4%$, $\rho_{\text{max}}^{5} = -28.7%$</td>
<td>$\rho_{\text{min}}^{5} = -57.3%$, $\rho_{\text{max}}^{5} = -29.3%$</td>
<td>$\rho_{\text{min}}^{5} = -62.9%$, $\rho_{\text{max}}^{5} = -28.5%$</td>
<td>$\rho_{\text{min}}^{5} = -54.6%$, $\rho_{\text{max}}^{5} = -28.6%$</td>
<td>$\rho_{\text{min}}^{5} = -47.7%$, $\rho_{\text{max}}^{5} = -27.9%$</td>
</tr>
<tr>
<td>6 m</td>
<td>$\rho_{\text{min}}^{6} = -55.1%$, $\rho_{\text{max}}^{6} = -30.5%$</td>
<td>$\rho_{\text{min}}^{6} = -57.0%$, $\rho_{\text{max}}^{6} = -26.3%$</td>
<td>$\rho_{\text{min}}^{6} = -62.6%$, $\rho_{\text{max}}^{6} = -35.2%$</td>
<td>$\rho_{\text{min}}^{6} = -54.4%$, $\rho_{\text{max}}^{6} = -27.5%$</td>
<td>$\rho_{\text{min}}^{6} = -47.4%$, $\rho_{\text{max}}^{6} = -26.4%$</td>
</tr>
<tr>
<td>9 m</td>
<td>$\rho_{\text{min}}^{9} = -16.1%$, $\rho_{\text{max}}^{9} = -3.2%$</td>
<td>$\rho_{\text{min}}^{9} = -68.4%$, $\rho_{\text{max}}^{9} = -23.7%$</td>
<td>$\rho_{\text{min}}^{9} = -22.4%$, $\rho_{\text{max}}^{9} = -18.9%$</td>
<td>$\rho_{\text{min}}^{9} = -83.9%$, $\rho_{\text{max}}^{9} = -32.4%$</td>
<td>$\rho_{\text{min}}^{9} = -244.5%$, $\rho_{\text{max}}^{9} = -25.0%$</td>
</tr>
</tbody>
</table>

Notes: The legend of the figures in the table is here.
Figure 11 shows that $\gamma_{\text{min}}^{\nu/l}$ of reticulated shell members is between -70.8% and -15.1%. The maximum $\gamma_{\text{min}}^{\nu/l}$ occurs when the scoreboard is 60 t and the sling length is 2 m. The minimum $\gamma_{\text{min}}^{\nu/l}$ occurs when the scoreboard is 40 t and the sling length is 9 m. When the scoreboard is more than 50 t and the sling length is less than 4 m, $\gamma_{\text{min}}^{\nu/l}$ value is not affected by scoreboard weight and sling length, and $\gamma_{\text{min}}^{\nu/l}$ value remains above -35%. With the sling length greater than 4 m, $\gamma_{\text{min}}^{\nu/l}$ value remains below -35%. When the scoreboard is less than 50 t, $\gamma_{\text{min}}^{\nu/l}$ value reaches the local peak. When the scoreboard is 30 t and the sling length is 4 m, $\gamma_{\text{min}}^{\nu/l}$ reaches the local minimum.

**Figure 11: Contour diagram of $\gamma_{\text{min}}^{\nu/l}$ values of reticulated shell members**

Figure 12 shows that $\gamma_{\text{max}}^{\nu/l}$ of support platform members are between -68% and 5200%, and the maximum $\gamma_{\text{max}}^{\nu/l}$ occurs when the scoreboard is 20 t and the sling length is 1 m. When the sling length is less than 4 m, $\gamma_{\text{max}}^{\nu/l}$ decreases gradually with the increase of scoreboard weight and sling length. $\gamma_{\text{max}}^{\nu/l}$ decreases faster with the increase of sling length and slowly with the increase of scoreboard weight. When the sling length is more than 4 m, $\gamma_{\text{max}}^{\nu/l}$ of support platform members is little affected by scoreboard weight and sling length, and $\gamma_{\text{max}}^{\nu/l}$ remains below 700%.

**Figure 12: Contour diagram of $\gamma_{\text{max}}^{\nu/l}$ value of platform members**

Figure 13 shows that $\gamma_{\text{min}}^{\nu/l}$ of support platform members are between -98.1% and -55.6%. The maximum $\gamma_{\text{min}}^{\nu/l}$ occurs when the scoreboard is 60 t and the sling length is 1 m. When the sling length is less than 3 m, $\gamma_{\text{min}}^{\nu/l}$ gradually decreases with the decrease of scoreboard weight. $\gamma_{\text{min}}^{\nu/l}$ reaches a local minimum when the scoreboard is 40 t and the sling length is 4 m. With the scoreboard weight greater than 40 t, $\gamma_{\text{min}}^{\nu/l}$ increases, and with the scoreboard weight less than 40 t, $\gamma_{\text{min}}^{\nu/l}$ of support platform members first increases and then decreases. When the sling length is between 5.5 m and 9 m, $\gamma_{\text{min}}^{\nu/l}$ of support platform members is little affected by scoreboard weight and sling length, and $\gamma_{\text{min}}^{\nu/l}$ remains below -80%.

**Figure 13: Contour diagram of $\gamma_{\text{min}}^{\nu/l}$ values of platform members**

In order to show the peak change rate $\gamma_{\text{max}}^{\nu/l}$ at different parts of the coupling system, contour diagrams of reticulated shell members and support
platform members are listed in Table 3. In general, when the scoreboard weight is 60 t and the sling length is 1 m and 2 m, \( \gamma_{j, \text{max}}^{w/d} \) of reticulated shell members are generally greater than those of other scoreboard weight and sling length. \( \gamma_{j, \text{max}}^{w/d} \) of some hoop members parallel to the x-axis direction are significantly greater than that of other members, and the values are more than 100\%, which indicates that the peak axial force of these members is greater when the scoreboard is flexibly suspended than the simplified case. This is because these members are consistent with the seismic wave input direction. On the whole, when the scoreboard is 40 t, \( \gamma_{j, \text{max}}^{w/d} \) of reticulated shell members are significantly less than that under other scoreboard weight, which indicates that the scoreboard has little effect on \( \gamma_{j, \text{max}}^{w/d} \) of reticulated shell members when the scoreboard is 40 t. In other cases, the influence of the scoreboard on \( \gamma_{j, \text{max}}^{w/d} \) of reticulated shell members is more uniform.

For support platform members, it is found that only a few members consistent with the seismic wave input direction have particularly large \( \gamma_{j, \text{max}}^{w/d} \) values, and most other support platform members have small \( \gamma_{j, \text{max}}^{w/d} \) values.

In conclusion, compared with the simplified case, the peak axial force of structural member under the flexibly suspended case cannot be ignored, and the influence of scoreboard weight and sling length cannot be ignored. The main conclusion is that the influence of the scoreboard on the peak axial force of support platform members is greater than that of reticulated shell members. The scoreboard has a certain enlarge effect on the axial force of some hoop members parallel to the input direction of seismic wave, and has little effect on other reticulated shell members. The scoreboard has a great enlarge impact on the peak axial force of some platform short members.

3.3. Influence of the center-hung scoreboard on node displacement

\[ d_{i, \text{max}}^{w/d} \] represents the peak displacement of the \( i \)th node when the scoreboard weight is \( w \) and the sling length is \( l \). Then, according to EQ. (17), the peak displacement change rate \( \eta_{i, \text{max}}^{\gamma} \) of the \( i \)th node can be obtained. \( d_{i, \text{min}}^{w/d} \) in EQ. (17) represents the peak displacement response of the \( i \)th node under the simplified case and the scoreboard weight is \( w \).

Through the analysis on \( \eta_{i, \text{max}}^{\gamma} \), the influence law of scoreboard weight and sling length on the peak displacement response of each node can be obtained.

\[
\eta_{i, \text{max}}^{\gamma} = \frac{d_{i, \text{max}}^{w/d} - d_{i, \text{min}}^{w/d}}{d_{i, \text{max}}^{w/d}} \tag{17}
\]

According to EQ. (18) and EQ. (19), the maximum \( \eta_{\text{max}}^{\gamma} \) and the minimum \( \eta_{\text{min}}^{\gamma} \) can be calculated, respectively, so as to discuss the overall impact of scoreboard weight and sling length on the peak displacement response of all nodes.

\[
\eta_{\text{max}}^{\gamma} = \max \left\{ \eta_{1, \text{max}}^{\gamma}, \eta_{2, \text{max}}^{\gamma}, \eta_{3, \text{max}}^{\gamma}, \eta_{4, \text{max}}^{\gamma}, \eta_{5, \text{max}}^{\gamma}, \eta_{6, \text{max}}^{\gamma} \right\} \tag{18}
\]

\[
\eta_{\text{min}}^{\gamma} = \min \left\{ \eta_{1, \text{max}}^{\gamma}, \eta_{2, \text{max}}^{\gamma}, \eta_{3, \text{max}}^{\gamma}, \eta_{4, \text{max}}^{\gamma}, \eta_{5, \text{max}}^{\gamma}, \eta_{6, \text{max}}^{\gamma} \right\} \tag{19}
\]

Since \( \eta_{\text{max}}^{\gamma} \) and \( \eta_{\text{min}}^{\gamma} \) of reticulated shell nodes and those of support platform nodes are quite different, they will be discussed separately. Figure 14 and Figure 15 respectively show contour diagrams of \( \eta_{\text{max}}^{\gamma} \) and \( \eta_{\text{min}}^{\gamma} \) of reticulated shell nodes varying with sling length and scoreboard weight. Figure 16 and Figure 17 show contour diagrams of \( \eta_{\text{max}}^{\gamma} \) and \( \eta_{\text{min}}^{\gamma} \) of support platform nodes, respectively.

Figure 14 shows that \( \eta_{\text{max}}^{w/d} \) of reticulated shell nodes are between 32.1\% and 125.4\%. The maximum \( \eta_{\text{max}}^{w/d} \) occurs when the scoreboard is 60 t and the sling length is 5 m. When the scoreboard is between 45 t and 60 t and the sling length is between 3.5 m and 5.5 m, \( \eta_{\text{max}}^{w/d} \) decreases rapidly with the decrease of scoreboard weight. When the scoreboard is 60 t and the sling length is 9 m, \( \eta_{\text{max}}^{w/d} \) is significantly larger than others. When the scoreboard is between 50 t and 60 t and the sling length is between 7.5 m and 9 m, \( \eta_{\text{max}}^{w/d} \) decreases rapidly with the decrease of scoreboard weight and sling length. When the sling length is less than 3 m, with the increase of scoreboard weight, \( \eta_{\text{max}}^{w/d} \) decreases first and then increases. When the scoreboard is 40 t and the sling length is 1 m, it reaches the local minimum. When the scoreboard is between 20 t and 50 t and the sling length is between 3 m and 9 m, \( \eta_{\text{max}}^{w/d} \) is not affected by sling length. \( \eta_{\text{max}}^{w/d} \) increases slowly with the decrease of scoreboard weight, but the overall value is basically maintained below 60\%.
**Table 3: Contour diagrams of peak change rate of axial force of the reticulated shell and the platform members**

<table>
<thead>
<tr>
<th>Weight</th>
<th>20 t</th>
<th>30 t</th>
<th>40 t</th>
<th>50 t</th>
<th>60 t</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td></td>
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<td>γ&lt;sub&gt;min&lt;/sub&gt;</td>
<td>γ&lt;sub&gt;max&lt;/sub&gt;</td>
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<td>2 m</td>
<td>[Diagram]</td>
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</tr>
<tr>
<td>γ&lt;sub&gt;max&lt;/sub&gt;</td>
<td>γ&lt;sub&gt;min&lt;/sub&gt;</td>
<td>γ&lt;sub&gt;max&lt;/sub&gt;</td>
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<td>γ&lt;sub&gt;max&lt;/sub&gt;</td>
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<td>4 m</td>
<td>[Diagram]</td>
<td>[Diagram]</td>
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<td>γ&lt;sub&gt;min&lt;/sub&gt;</td>
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<td>5 m</td>
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<td>6 m</td>
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<td>9 m</td>
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</tr>
</tbody>
</table>

Notes: The legend of the figures in the table is here.
Figure 14: Contour diagram of $\eta_{wl}^{\text{reticulated shell nodes}}$

Figure 15: Contour diagram of $\eta_{wl}^{\text{reticulated shell nodes}}$

Figure 15 shows that $\eta_{wl}^{\text{min}}$ is between -52.1% and -13.3%. The maximum $\eta_{wl}^{\text{min}}$ occurs when the scoreboard is 60 t and the sling length is 2 m, and the minimum $\eta_{wl}^{\text{min}}$ occurs when the scoreboard is 20 t and the sling length is 1 m. When the scoreboard weight is greater than 40 t, the $\eta_{wl}^{\text{min}}$ value decreases with the decrease of scoreboard weight. When the scoreboard is between 50 t and 60 t, the $\eta_{wl}^{\text{min}}$ value decreases slowly with the increase of sling length. When the scoreboard is between 40 t and 50 t, $\eta_{wl}^{\text{min}}$ value is very little affected by the sling length. When the scoreboard is less than 40 t, $\eta_{wl}^{\text{min}}$ value increases slowly with the increase of sling length.

Figure 16 shows that $\eta_{wl}^{\text{max}}$ of support platform nodes are between -54% and 39.5%. The maximum $\eta_{wl}^{\text{max}}$ occurs when the scoreboard is 60 t and the sling length is 2 m, and the minimum $\eta_{wl}^{\text{max}}$ occurs when the scoreboard is 20 t and the sling length is 1 m. When the scoreboard is greater than 40 t, the $\eta_{wl}^{\text{max}}$ value decreases with the decrease of scoreboard weight. When the scoreboard is between 50 t and 60 t, the $\eta_{wl}^{\text{max}}$ value decreases slowly with the increase of sling length. When the scoreboard is between 40 t and 50 t, $\eta_{wl}^{\text{max}}$ value increases first and then decreases with the decrease of scoreboard weight. When the sling length is between 2.5 m and 5 m, $\eta_{wl}^{\text{max}}$ value increases slowly with the decrease of scoreboard weight.

Figure 17 shows that the $\eta_{wl}^{\text{min}}$ values of the platform nodes are between -58.2% ~ 22.5%. The maximum value of $\eta_{wl}^{\text{min}}$ occurs when the scoreboard is 60 t and the sling length is 2 m, and the minimum value of $\eta_{wl}^{\text{min}}$ occurs when the scoreboard is 20 t and the sling length is 1 m. When the scoreboard weight is greater than 40 t, the $\eta_{wl}^{\text{min}}$ value decreases with the decrease of
of the scoreboard weight. When the scoreboard weight is between 50 t and 60 t, the $\eta_{\min}^{\nu,l}$ value decreases slowly with the increase of the sling length. When the scoreboard is between 40 t and 50 t, the $\eta_{\min}^{\nu,l}$ value is little affected by the sling length. When the sling length is between 1 m and 2.5 m, the $\eta_{\min}^{\nu,l}$ value is less affected by the scoreboard weight. When the sling length is between 5 m and 9 m, the $\eta_{\min}^{\nu,l}$ value increases slowly with the decrease of the scoreboard weight.

![Figure 17: Contour diagram of $\eta_{\min}^{\nu,l}$ values of platform nodes](image)

Table 4 displays the peak displacement change rate $\eta_{\max}^{\nu,i}$ at different parts of the coupling system. Overall, $\eta_{\max}^{\nu,i}$ of reticulated shell nodes near the supports are positive and the value is large, while $\eta_{\max}^{\nu,i}$ of the nodes in the central part of the reticulated shell is mostly negative or small positive, which indicates that the peak displacement near the supports is larger and the displacement peak of the nodes in the central part of the reticulated shell is smaller in the flexibly suspended case than that in the simplified case. For support platform nodes, when the scoreboard is between 50 t and 60 t, $\eta_{\max}^{\nu,l}$ show small positive value, and when the scoreboard is less than 50 t, the $\eta_{\max}^{\nu,l}$ values are negative, which indicates that in most cases, the peak displacement of support platform nodes becomes smaller when the scoreboard is flexibly suspended.

To sum up, based on the analysis on the values and spatial distribution of $\eta_{\max}^{\nu,l}$ and $\eta_{\min}^{\nu,l}$, it is found that compared with the simplified case, the peak displacement in the case of flexibly suspension are quite different, and the influence of the scoreboard weight and the sling length cannot be ignored. The main finding is that the influence of center-hung scoreboard on the peak displacement of reticulated shell nodes is greater than that of support platform nodes. In most cases, compared with the simplified case, the peak displacement of nodes near the supports of reticulated shell is larger when the scoreboard is suspended. The peak displacement of nodes in the center of the reticulated shell are relatively small. The flexibly suspended scoreboard has little influence on the peak displacement of nodes on the support platform as a whole.

4. DISCUSSION

Combined with the seismic analysis results and the structural form of the coupling system, the reasons for the seismic responses variation law with center-hung scoreboard can be obtained. Firstly, the center-hung scoreboard has the greatest impact on the axial force and the least impact on the node displacements. Furthermore, the seismic waves are input from the supports, and the connections between the support platform members and the members in the central part of the reticulated shell play a certain damping role. Hence, the seismic responses of the nodes near the supports are greater than those of the nodes in the central part of the reticulated shell. Secondly, the peak axial force of some ring members and support platform members parallel to the seismic wave input direction is significantly larger than that of others. Finally, since the scoreboard is directly suspended on the support platform, the peak axial force of the support platform members in the flexibly suspended case is significantly greater than that in the simplified case. Since the stiffness of the support platform is greater than that of the reticulated shell, the influence of center-hung scoreboard on the peak displacement of reticulated shell nodes are greater than those of the support platform nodes. In addition, the seismic responses of the coupling system are greatly affected by the scoreboard weight and the sling length. In future engineering design, the scoreboard weight and the sling length should be seriously concerned.
Notes: The legend of the figures in the table is here.
Other design parameters of the single-layer reticulated shell including structural span, rise to span ratio, grid patterns, member sections have not been included. In addition, only one construction site characteristic is considered, the influence of the construction site is expected to be further analyzed. Furthermore, vertical seismic action and traveling effect of the earthquake should be considered for future seismic response analysis. Hence, more work is expected to provide useful guidelines for the long-span spatial structure with a flexibly suspended center-hung scoreboard.

5. CONCLUSION

(1) Compared with the case where the center-hung scoreboard is simplified as fixed mass on support platform, the maximum change rate of the peak displacement, the maximum change rate of the peak acceleration and the maximum change rate of the peak axial force are all more than 100% when the center-hung scoreboard is flexibly suspended. The seismic response difference between the two cases is significant, and the treatment method of simplifying center-hung scoreboard as fixed mass of support platform during the seismic analysis is dangerous. The sling length and the scoreboard weight have significant effects on the peak displacement, the peak acceleration and the peak axial force. The envelope values under different sling length and different scoreboard weight should be taken as the seismic response analysis results.

(2) Compared with the case where the center-hung scoreboard is simplified as fixed mass on support platform, the peak acceleration of the nodes near the supports of the reticulated shell is larger and the peak acceleration of the nodes in the center of the reticulated shell is smaller when the center-hung scoreboard is flexibly suspended. The change rate of the peak acceleration of center-hung scoreboard connecting nodes is significantly larger than that of other nodes on the support platform.

(3) The center-hung scoreboard has a greater impact on the peak axial force of some support platform members than on that of reticulated shell members. The center-hung scoreboard has a certain enlarge effect on axial force of some hoop members parallel to the input direction of seismic wave, and has a small impact on the peak axial force of other reticulated shell members. The center-hung scoreboard can reduce the peak axial force of some members on support platform, and also have the peak axial force of other support platform members increased significantly.

(4) The influence of the center-hung scoreboard on the peak displacement of the nodes on the reticulated shell is greater than that of the support platform. In most cases, the peak displacement of nodes near the supports are larger when the center-hung scoreboard is flexibly suspended, but the peak displacement of nodes in the central part of reticulated shell are relatively small. The center-hung scoreboard has a greater influence on the supports of the reticulated shell, but has little influence on those of the support platform.

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REFERENCES


[23] Xin Huang. Study on Seismic Design Methods for Long-Span Spatial Structures, Tianjin University, Tianjin, 2007:3.


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