RUDN university

Российский университет дружбы народов

PhD Dissertation Presentation

Title: ***Structural Design and Construction of Deployable Formwork for Concrete Shell Structures:*** Use of Flexible Membrane and Automized Pin Supports

2.1.1 Building Structures, Buildings and Structures

May 20, 2026

Presenter:
Damir Habte Yohannes
1042205016

Academic Advisor:
Rynkovskaya Marina (PhD.)

PhD 4th Year
Department of Civil Engineering, Engineering Academy
RUDN University, Moscow, Russia

Presentation Outline

Background and Research Relevance
Concrete Shell Structures; Problem Statement; Relevance of Research

1 **Structural Analysis and Design**
Support pins · grid plates · EPS-cement membrane · FEA and buckling

2 **Automation and Support Erection**
Python height mapping · Arduino control · motorized pin actuation

3 **Experimental Prototype Dome /**
Fabricated supports · flexible membrane · dome assembly · concrete casting

4 **Economic and Feasibilityof Practical Applicability**
Time/cost comparison · reuse cycles · scalability · industry application

5 **Conclusion and Recommendations**
Research contribution · provisions defended · future development

Background: Concrete Shell Structures

Context

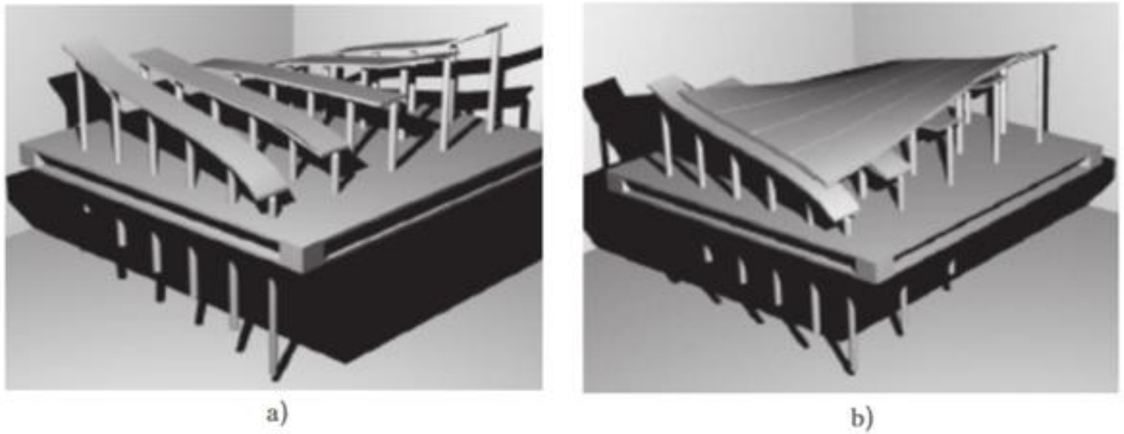
Why shell formwork remains a critical construction problem?

Concrete shell construction had a "golden period" from 1925 to 1975, but declined due to formwork cost and labor intensity.

Challenges of Shell Structure Formwork

- High cost,
- Material waste,
- Labor intensity,
- Reusability limit

The L´Oceanogràfic at Valencia, Spain (Candela, 2001). (Source: [Tomas and Marti 2010, [8]).



Goal and Objective of the Research

Research

Effect of Formwork imperfection on Shell Structural Failures

The complexity of formwork of shells demands skilled and intense labour, leading to errors on shape formation diverting from the designed model, risking the structural stability of the structure. And this study investigates a new formwork system which is structurally stable and with computer controlled shape form creation.

Main Goal

To develop a Structurally stable and economically affordable formwork system of concrete Shell structures that can support different shapes.

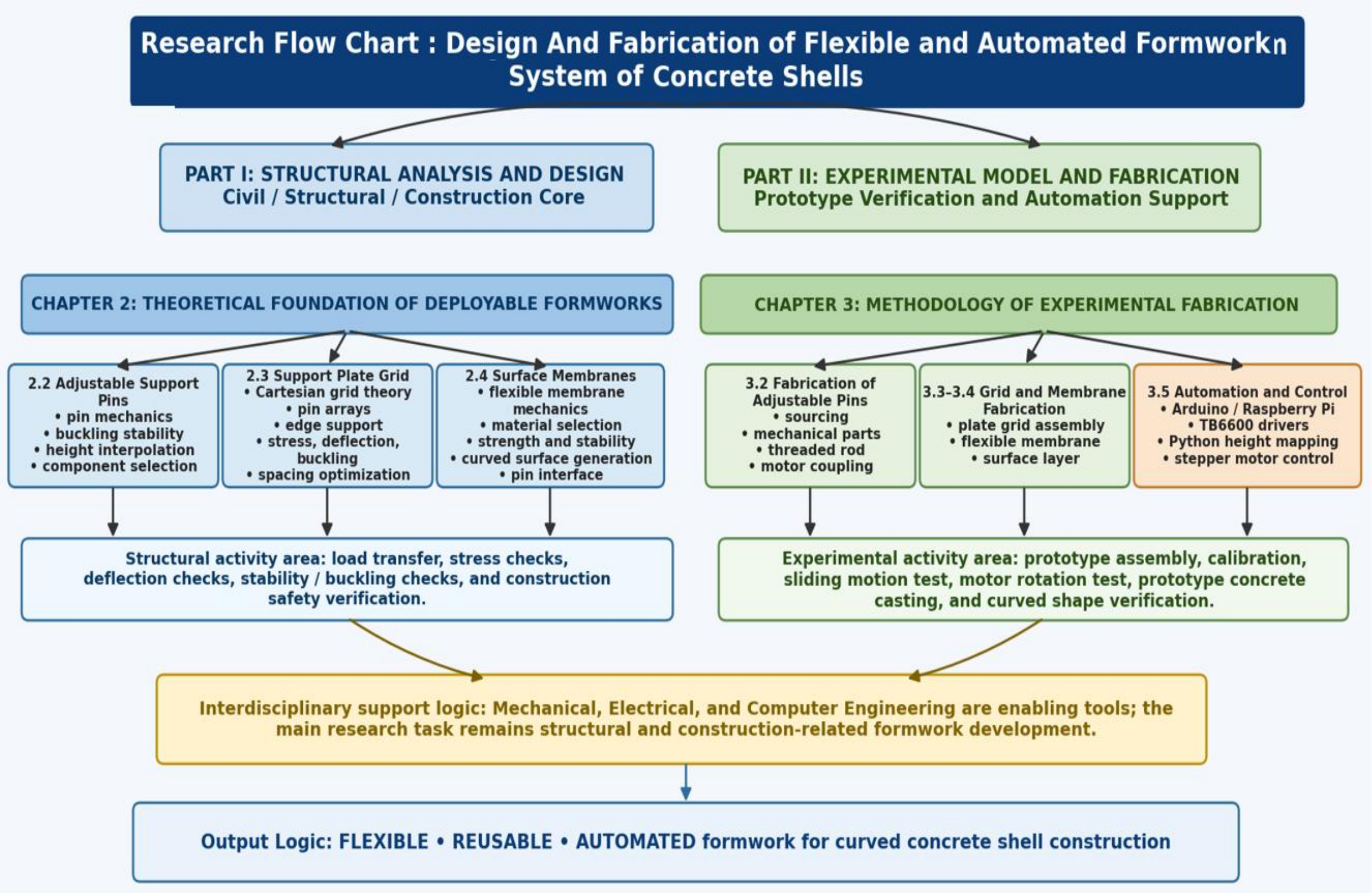
The goal is achieved through the:

1. Automation of the vertical supports to be adjustable and reusable
2. Application of Python Programming to generate 3D models of curved surfaces and mathematical interpolation to determine height mapping
3. Development of flexible and reusable curves surface membranes
4. To Validate the output through fabrication and testing of experimental prototype
5. Recommendation on the extension of the innovation through further applicability studies

Methodology

Methods

Integrated analytical, numerical and experimental research workflow



Research flow chart used for design and fabrication framework

Automation

Python, Arduino, motors

Structural Analysis

Stresses Deflection Buckling,

Literature review

Research gaps in Formwork systems,

Fabrication

Pins, grids, membranes, prototype

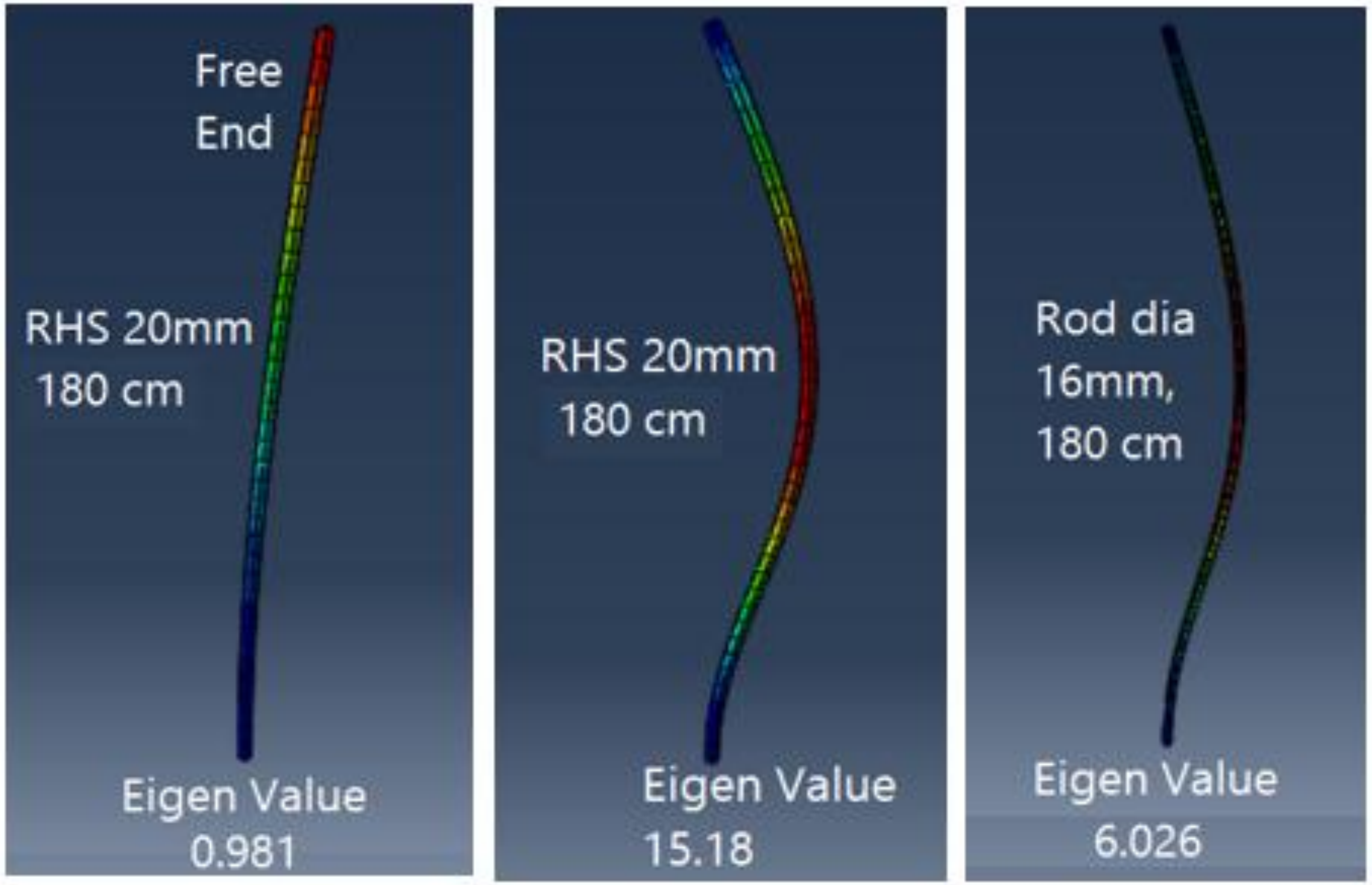
Feasibility

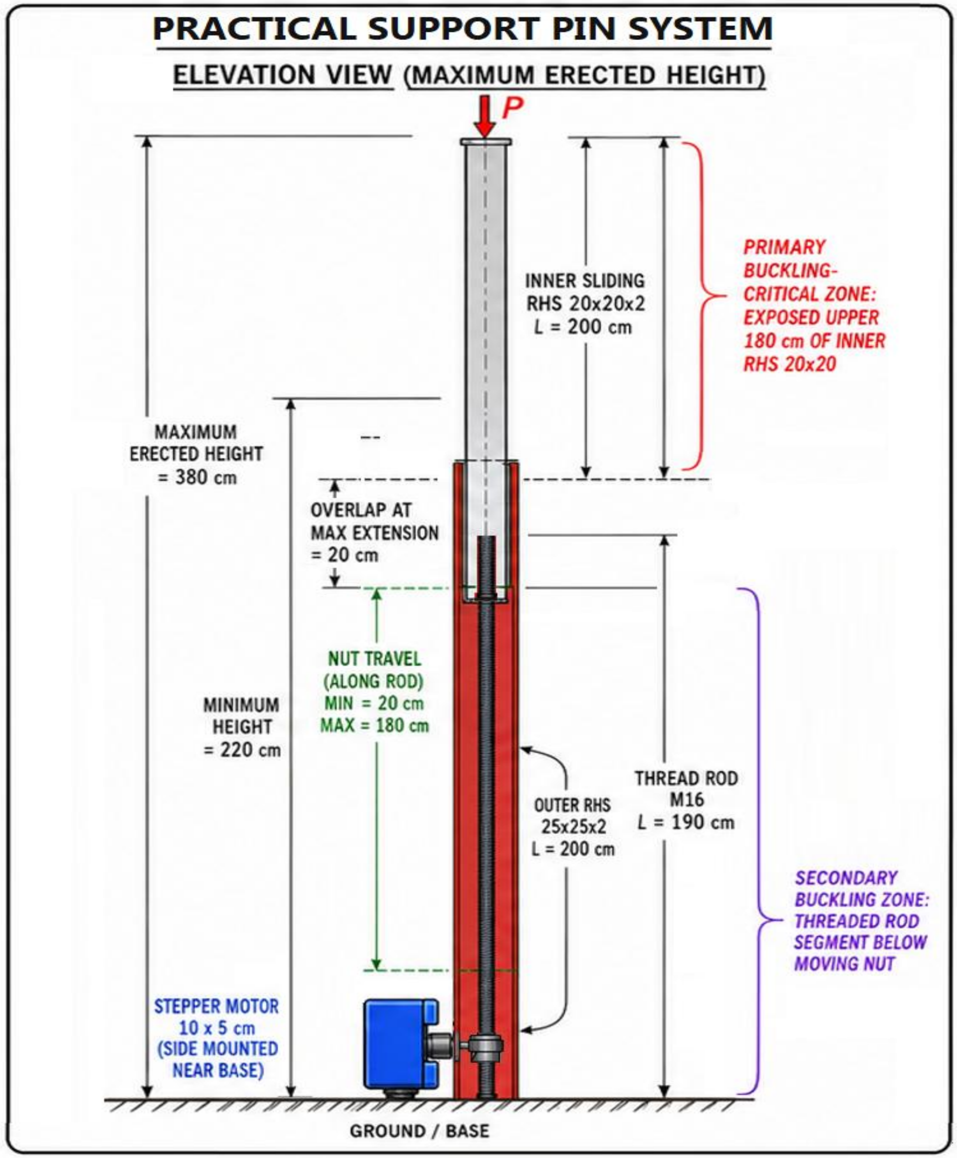
Cost, time, sustainabil ity

1. Structural Analysis and Design

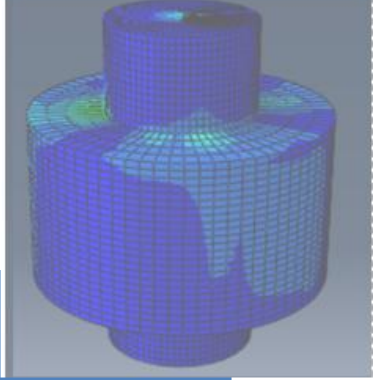
1.1 Design and Fabrication of Adjustable Support Pins

- Abaqus analysis on support pin on stresses, buckling and deflection





1. Structural Analysis and Design

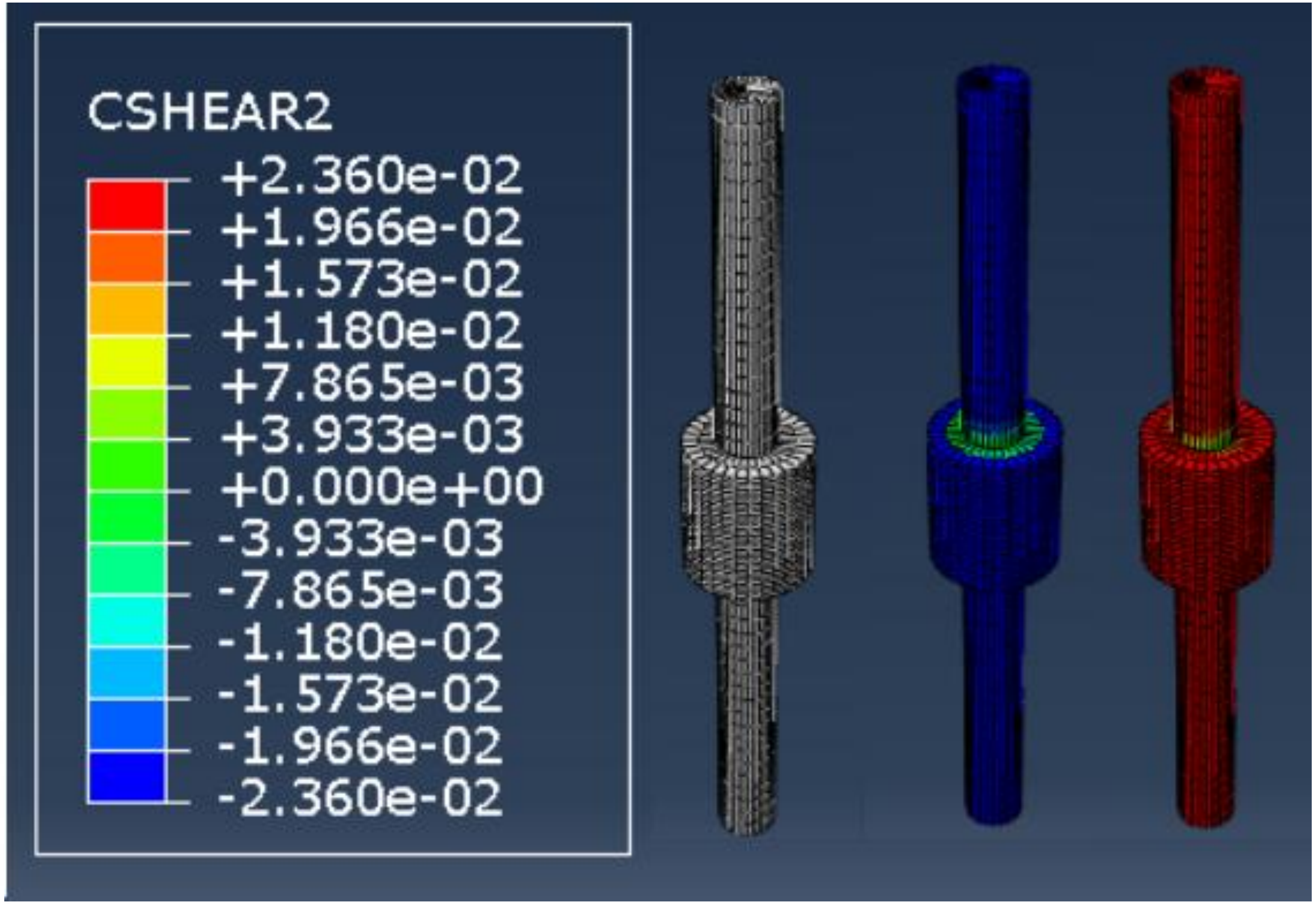


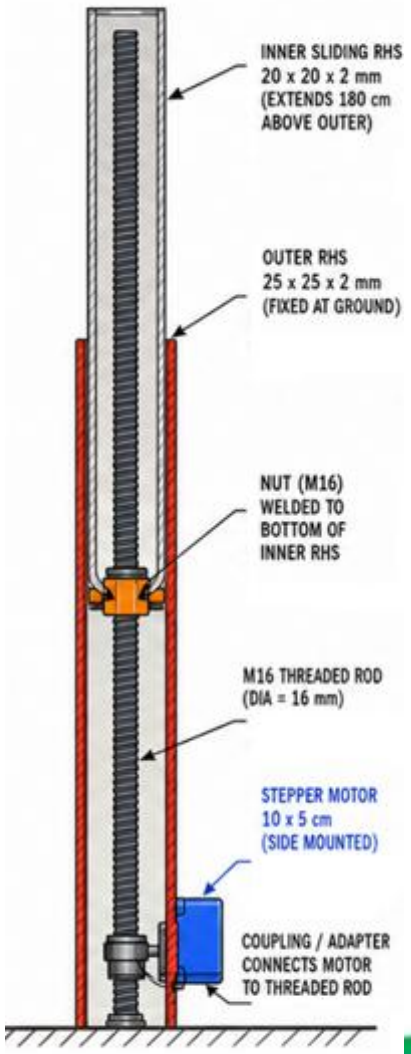
Summary of Structural Analysis Results

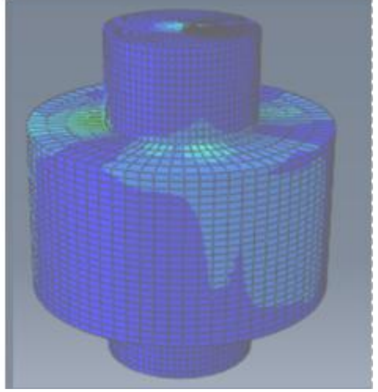
Model / Case	Max S Mises, MPa	Main axial stress S22, MPa	Main U / mode value	Eigen-value	Critical load (N) P_{cr}	Interpretation
RHS 20 mm, free top	1.421	±1.393	U1 mode max = 1.000	0.9815	490.75	Buckles slightly below 500 N; free-top not recommended
M16 threaded rod	5.643	±5.643	U1 max =1.0; U3 min = −0.096	6.0263	3013.15	Safe against buckling under 500 N; secondary member
RHS 20 mm, restraining top grid	11.64	±11.65	U1 mode max = 1.000; U3 min = −0.4206	15.183	7591.5	Much safer; top lateral restraint strongly improves buckling capacity

1. Structural Analysis and Design

Result of contact shear stress between threaded rod and nut



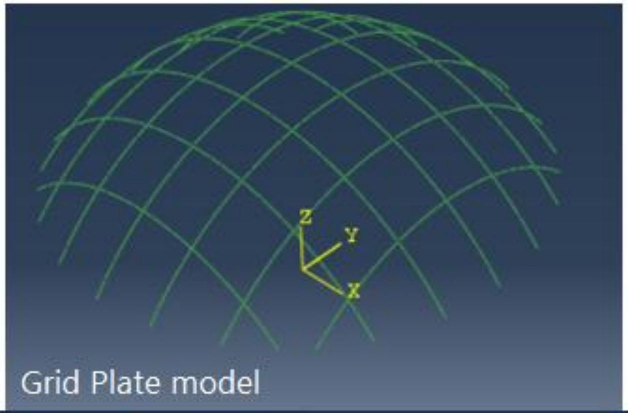


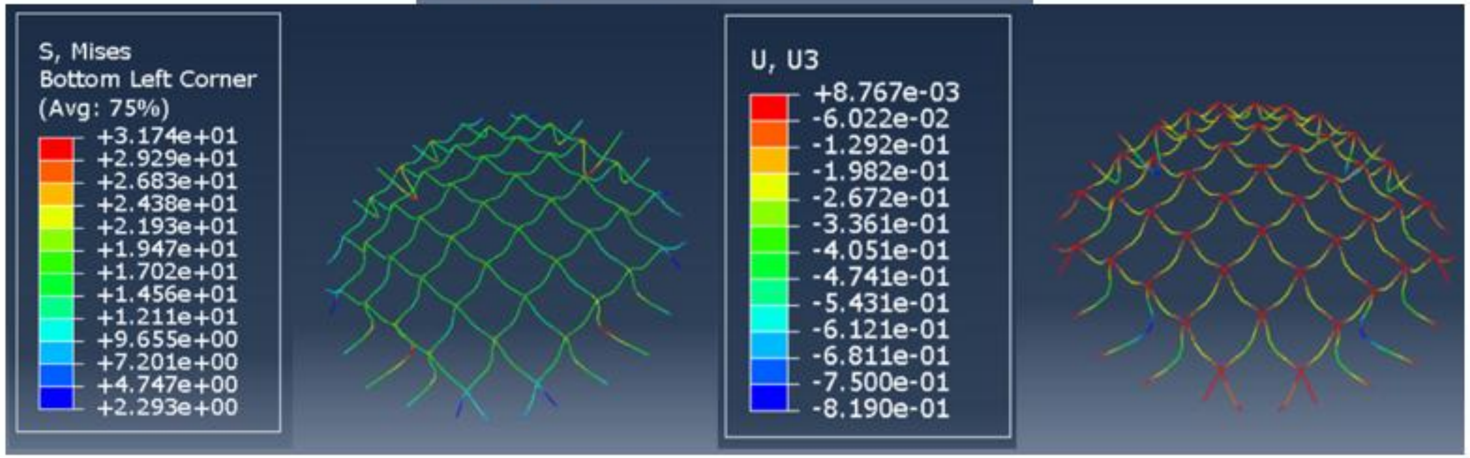


1. Structural Analysis and Design

1.2 Structural Analysis of Grid and Plate System

- Plate width 30mm; Thickness: 3mm; E = 210 Gpa; v = 0.3; σ y = 250 Mpa;
- Abaqus analysis on support pin on stresses, buckling and deflection





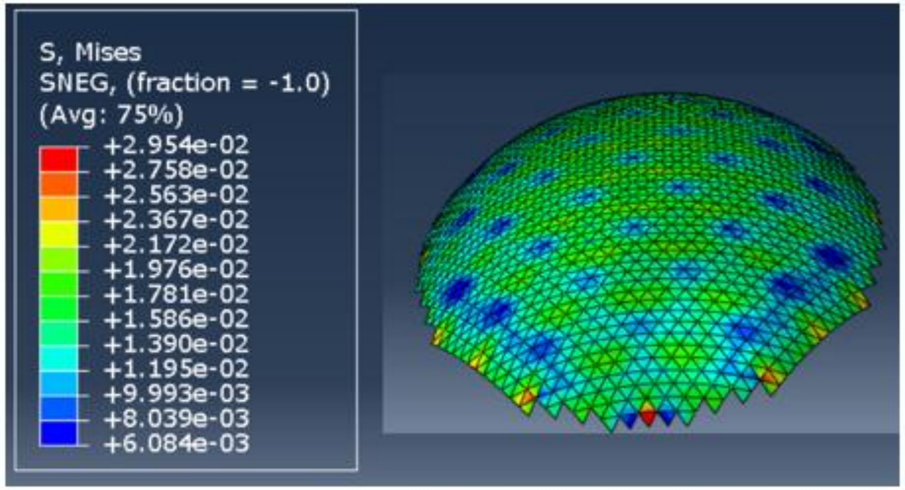
S.N	Parameter	Result
1.	Maximum Stress	31.74 MPa
2.	Maximum deflection	-0.819 mm

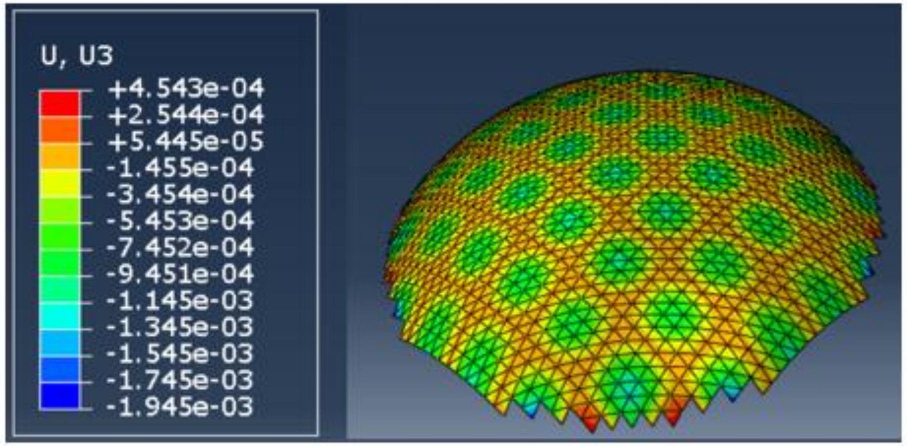
1. Structural Analysis and Design

1.3 Structural Analysis of EPS-Concrete mix membrane

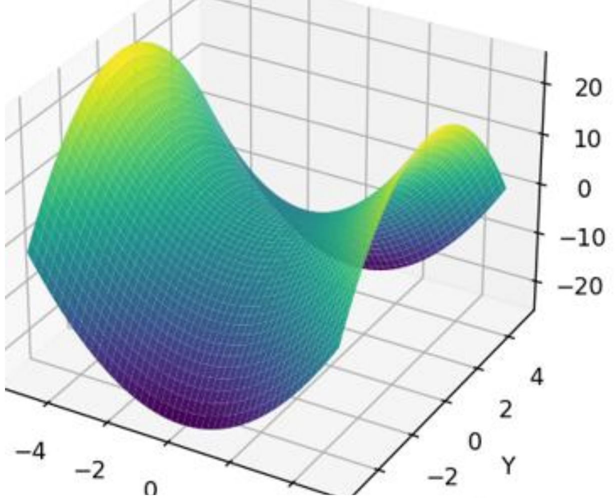
- Thickness: 30 mm; E = 5 Gpa; v = 0.3; σ_{ec} = 12 Mpa; Load: 2.88 kN/m2
- Abaqus analysis on support pin on stresses, buckling and deflection

S.N	Parameter	Result
1.	Maximum Stress	0.0254 MPa
2.	Maximum deflection	-0.0019 mm

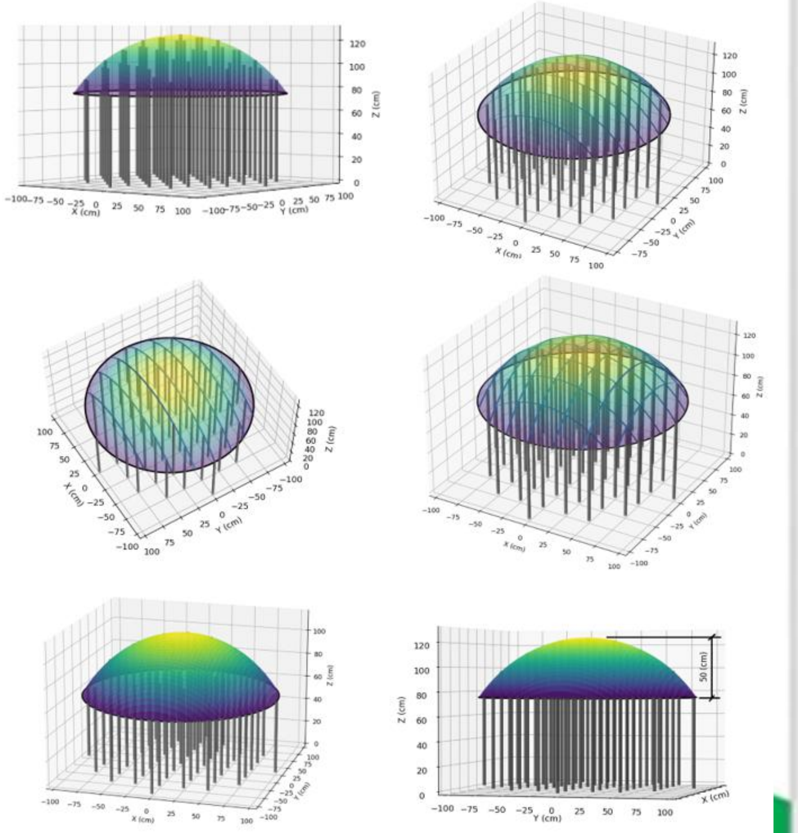


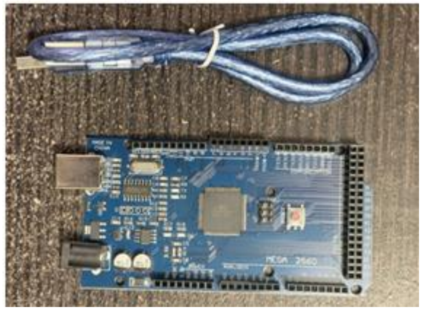


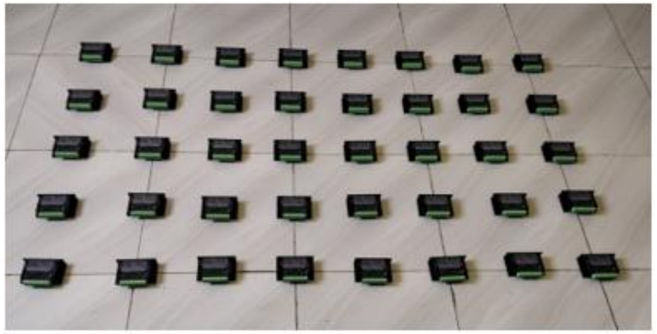
2. Automation of Formwork Supports



- 2.1 Surface Generation Using Python programming
- 2.2 Python Coding to model and map heights
- 2.3 Use of Arduino Uno, Motor Driver and Stepper Motor





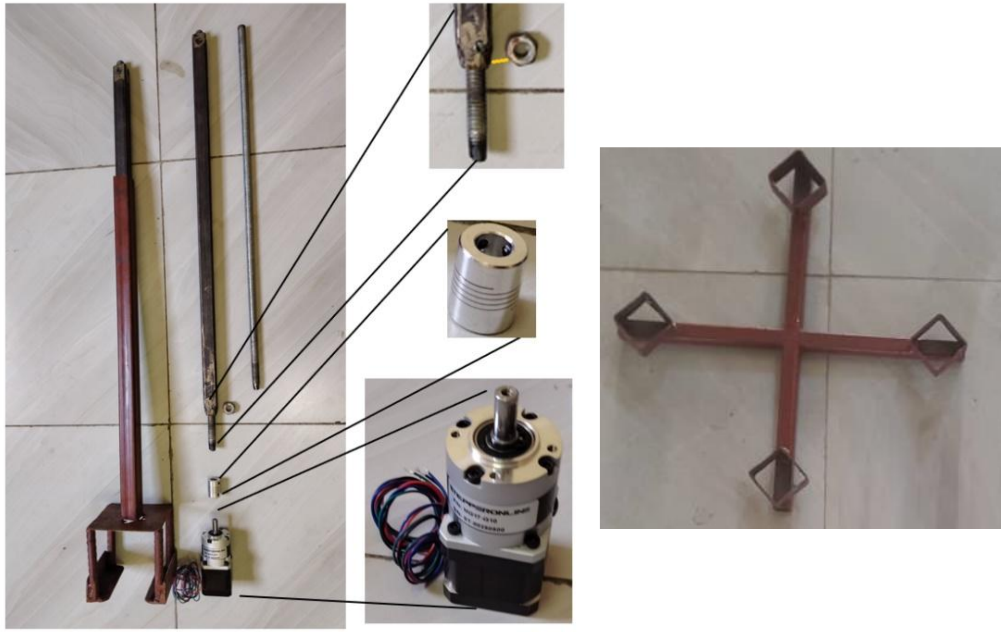


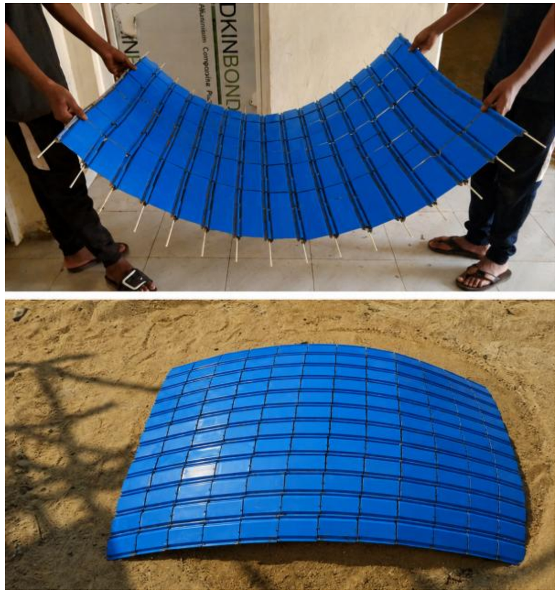
a)

b)

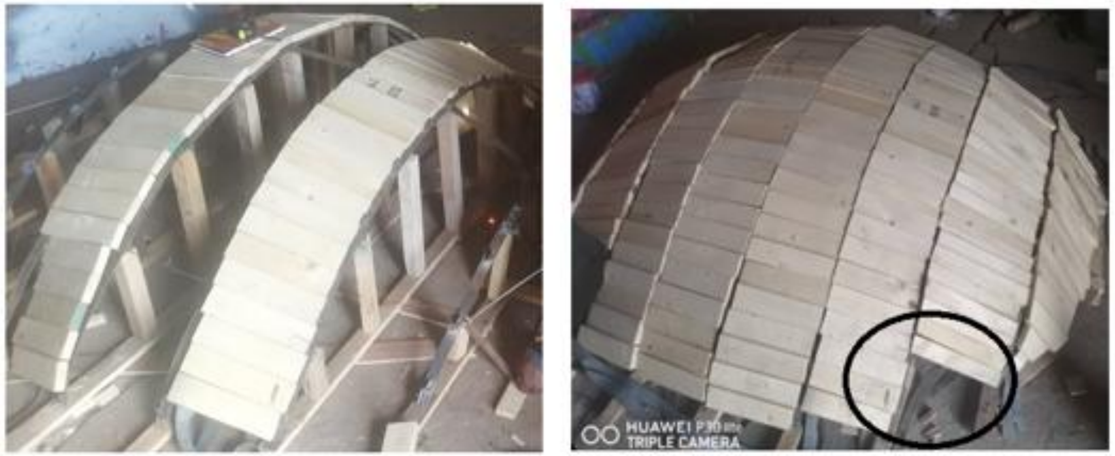
3. Fabrication of Experimental Components

- 3.1 Support Pin Fabrication
- 3.2 Fubrication of Flexible Timber Surface Membrane Support
- 3.3 Fabrication of Flexible Metal Surface Membrane Support





Timber membrane



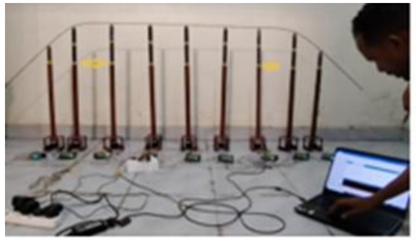
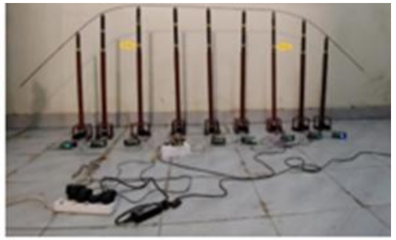
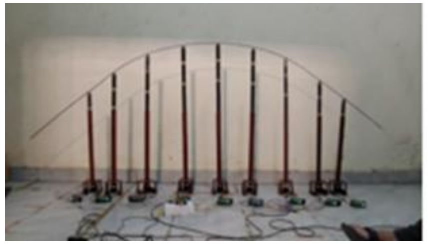
Steel flexible membrane

3. Fabrication of Experimental Components

3.4 Testing of Adjustable Pin Support – Positive and Negative Curves






3. Fabrication of Experimental Components

3.5 Testing Adjustable Support Pins for 3D erection

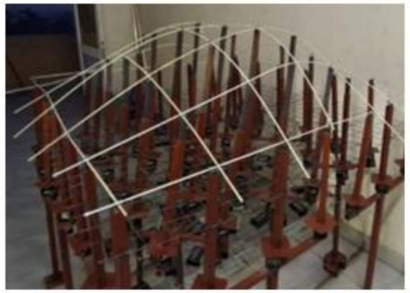










Prototype Concrete Casting

Formwork assembly, surface finishing and casting activity

Formwork assembly and surface finishing

Prototype concrete mixing and casting

Economic Feasibility

Feasibility

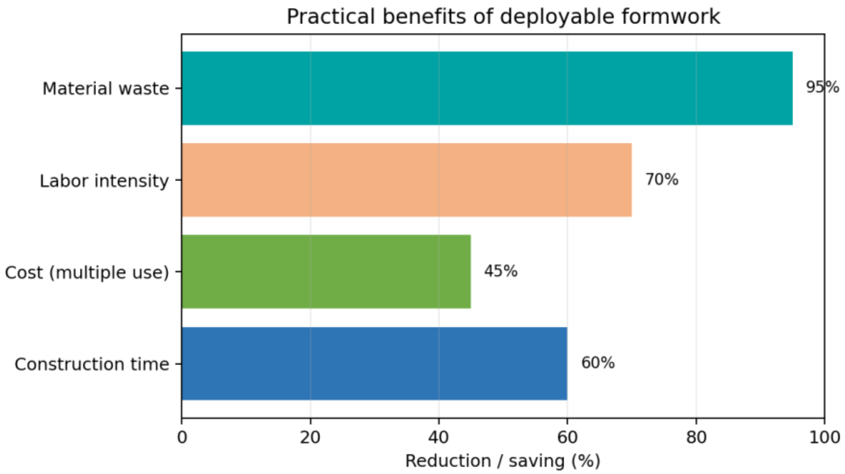
Cost structure and reuse advantage

Fabrication uses conventional low-risk processes: cutting, drilling, welding, light machining and painting/galvanizing.

Estimated fabrication and assembly cost per unit: 20–30 USD.

Total motorized adjustable pin cost: 116–193 USD; average about 154 USD.

Bulk procurement can reduce final cost to approx. 116 USD per support.



Component	Cost range
NEMA 23 stepper motor	30–50 USD
Planetary gearbox	20–40 USD
Motor driver	25–40 USD
Coupling, bearings, wiring	8–15 USD

Economic principle

Higher initial cost is offset by reusability, faster setup and lower labor demand.

Adjustable Formwork Construction Estimation

Feasibility

Motorized support pin method for 10 m dome case

No.	Activity	Time
1	Support pin erection	1–1.5 days
2	Height calibration	0.25 day
3	Automated shaping	< 0.25 day
4	Horizontal bracing	0.5–1 day
5	Membrane installation	1–1.5 days
	Total	2.5–3.5 days
6	Dismantling time	1–1.5 day

Traditional Formwork Construction Estimation

Feasibility

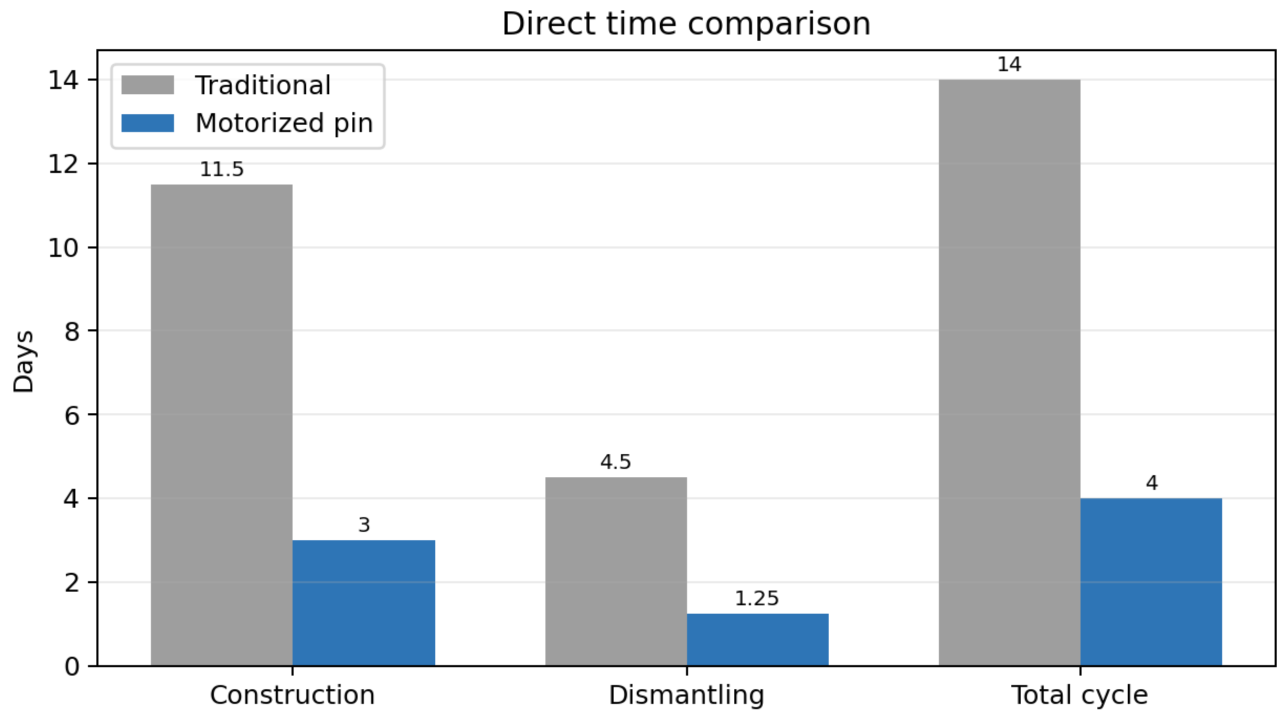
Conventional curved rib and prop method for 10 m dome case

No.	Activity	Time
1	Vertical and inclined prop erection, bracing	2.0–3.0 days
2	Height variation: measuring and setting across dome	1–1.5 days
3	Fabrication of curved ribs/profiles	2–3 days
4	Installation of curved ribs	2–3 days
5	Membrane surface installation	2–3 days
	Total	9–14 days
7	Dismantling time	2–3 days

Direct Time Comparison

Feasibility

Traditional vs. motorized pin formwork



Item	Traditional	Motorized pin
Formwork construction	9–14 days	2.5–3.5 days
Dismantling	4–5 days	1–1.5 days
Total cycle	11–17 days	4 days
Geometry setting	Manual	Automated
Reusability	Low	Very high

Practical Implementation Feasibility

Feasibility

Advantages, limitations and application areas

Advantages

Structurally stable, Reusable hardware, rapid reconfiguration, digital geometry setting, high repeatability, lower material waste and shorter construction time.

Limitations

Higher initial capital cost, electrical commissioning, protection of motors against dust/moisture and need for scale-up validation.

Applications

Curved Surface Shells, and free-form roofs. Unique architectural objects, restoration works

Scientific Novelty and Significance

Contributions

Main research contributions

Structurally stable Flexible and automated deployable formwork for concrete shells.

Integrated structural analysis and automated shape generation.

Combined system of vertical support pins, grid plates and flexible membranes.

FEA-based evaluation of support pins, grid plates and EPS-cement membrane.

Arduino-based distributed control with Python surface interpolation.

Positioning resolution 0.0009375 mm and reconfiguration time < 200 s.

Open-source Python + Arduino control framework for further academic and industry development.

Prototype proves multidisciplinary integration serving a civil/structural engineering objective.

Reliability and Approbation

Defense

Verification methods and dissemination

Structural Reliability

Results were verified through theoretical calculations, FEA, prototype fabrication, calibration and testing. Structural reliability was checked through stress, buckling, deflection and load-bearing analyses.

Experimental Validation

Motion, accuracy, repeatability, membrane behavior and full-system tests confirmed prototype performance within the study scope.

Approbation

Main provisions were reported at international conferences: ICMSTech-2024 (Kursk), and the International Scientific and Practical Conference in Almaty, Kazakhstan, 2025. 4th BRICS SciTech Forum (RUDN, Moscow, 2023),

Conclusions and Recommendation

Conclusion

Research outcomes and implementation potential

The deployable formwork system achieved high structurally stability, precision, adaptability and sustainability.

Flexible and automated pin supports provided precise alignment and load distribution.

The system reduce formwork construction time by 55–65% and cost by 40–50% with multiple uses.

Reusable components and digital reconfiguration reduce material waste and improve efficiency.

Further research should optimize membrane design and protect motors from moisture and dust.

A full software package is recommended for arbitrary geometry formwork design.

Scalability and standardization are required for full-scale construction deployment.

The system has potential for unique architecture, restoration and rapid construction.

Provisions Submitted for Defense

Defense

Key claims supported by analysis and testing

Vertical support pins can be designed to maintain stability under axial compression and buckling

Support plate grid transfers load while controlling stress and deflection.

25 cm pin spacing with grid plates and wooden panels achieves acceptable surface accuracy.

Mathematical shell geometry can be converted into physical pin heights.

Automation accurately adjusts pin heights using Python, Arduino, motor drivers and stepper motors.

Motorized system reduces formwork construction time and material waste compared with traditional.

Practical feasibility is justified by scalability, cost-effectiveness and low-skill deployment potential.

Work bridges structural engineering, material science, electrical, programming and automation.

Relevance to Specialty 2.1.1

Context

Building Structures, Buildings and Structures

Relevant to development and improvement of rational load-bearing and enclosing structural systems.

Focus remains civil-engineering and construction-oriented.

Mechanical, electrical and programming components are supporting tools, not the main research object.

Direct link to structural formwork supports, shell surface generation and practical implementation.

The research is relevant to **'Building Structures, Buildings and Structures (code 2.1.1)' -** passport No. 8 'Development of new and improvement of rational types of load-bearing and enclosing structures, as well as structural solutions for buildings and facilities' and partially to passport No. 4, 3 and 2.

Dissertation scope

Structural analysis + experimental fabrication of a deployable formwork prototype.

Primary outcomes

Stability, Cost/time reduction, reusable components, automated geometry setting and reduced material waste.

Practical impact

Potential revival of concrete shell applications in architecture and engineering.

RUDN university

Российский университет дружбы народов

Thank You

Questions and Discussion