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Parametric Design in Structural Optimization: Long-Span Roof Optimization through Generative Processes

Siddharth Gautam[1], Chhabi Lal Singh[2]

[1]PG Student, Department of Civil Engineering, JS University, Sikohabad, U.P
[2]Assistant Professor, Department of Civil Engineering, JS University, Sikohabad, U.P

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Abstract - *This paper explores the application of generative design technology and parametric modeling in the structural optimization of architectural forms. Focusing on a long-span roof gridshell structure, this study utilizes computer-aided design tools to demonstrate how varying structural components can achieve optimal topology, mass, and displacement. By integrating parametric modeling (Rhinoceros/Grasshopper) with Finite Element Analysis (Karamba3D) and multi-objective optimization algorithms (Galapagos/Octopus), this research highlights the relationship between structural parameters and the variation of optimal design outcomes*.

Keywords: Generative Design, Parametric Modeling, Structural Optimization, Topology Optimization, Gridshell, Finite Element Analysis

1. INTRODUCTION:

Building Simulation Optimization (BSO) is increasingly utilized in conceptual design phases to improve overall building performance and assist decision-making. In structural design, optimization can be categorized into three distinct methods:

- **Sizing Optimization:** Adjusting specific cross-sectional areas or material thicknesses while maintaining the overall shape.
- **Shape Optimization:** Controlling the domain or contour of a structural boundary without altering its internal connectivity.
- **Topology Optimization:** Determining the optimal connectivity among nodes by progressively removing unnecessary elements from a dense ground structure to minimize weight and maximize stiffness.

Applying mathematical optimization to architectural design is historically difficult due to the co-evolving and "wicked" nature of architectural problems. However, integrating optimization directly into bounded sub-problems can enhance the designer's capabilities and yield highly efficient structures.

2. GENERATIVE AND PARAMETRIC DESIGN FRAMEWORK:

The shift from traditional passive design to computational design requires differentiating between two primary methodologies:

Parametric Design: A process based on algorithmic thinking where symbolic parameters and rules constrain the design geometry. The user manually adjusts these parameters (such as positioning or dimensions) to evaluate model variations.

Generative Design (GD): A more autonomous process where algorithms generate and propose a multitude of design configurations that satisfy specific constraints and maximize a goal function. GD software uses artificial intelligence to mimic evolutionary processes, iteratively exploring a solution space to find optimal results with minimal human intervention.

3. METHODOLOGY:

The case study focuses on developing an optimal topology for a steel long-span roof utilizing a grid shell structure. Grid shells are continuous structural surfaces where material has been removed to create a grid pattern, relying on double curvature and in-plane shear stiffness to efficiently carry loads.

3.1. Parametric Modeling

The base geometry was developed using Rhinoceros 3D and its visual programming plugin, Grasshopper. The roof structure's foundational curves were generated using catenary equations. The parametric equations defining the catenary are expressed as:

$$x(t) = t$$
$$y(t) = a\cosh(\frac{t}{a})$$

To construct the diagrid roof, a network surface was evaluated, and parameters determining the column quantities, branch divisions, and node positions were converted into "gene pools" to enable algorithmic variation.

3.2. Finite Element Analysis (FEA)

Karamba3D was employed for interactive, parametric finite element calculations.

Materials & Sections: The structural material assigned was S450 grade stainless steel, which possesses high ductility and yield strength. Hollow circular cross-sections were applied to the columns and grid structure due to their strong torsional capacity, resistance to buckling, and aesthetic finish.

Load Conditions: The structure was subjected to gravity loads (self-weight) and wind loads. The basic wind velocity pressure was calculated according to Eurocode standards utilizing the formula

$$q_b = \frac{1}{2} \cdot \rho \cdot v_b^2.$$

Upwind and downwind pressure coefficients were conservatively estimated at -2.93 kN/m^2 and -1.17 kN/m^2, respectively.

3.3. Multi-Objective Optimization:

Structural topology optimization was conducted to maximize structural stiffness (minimize compliance) while monitoring the overall mass. The compliance objective function is defined as:

$$Minimize : C = F^T \times u(x)$$

(Where C is compliance, F^T is the applied load vector, and u(x) is the displacement vector).

The optimization was executed utilizing Octopus, a multi-objective evolutionary optimization tool that searches for optimal trade-offs between multiple goals using the Pareto-Principle.

4. RESULTS AND DISCUSSION:

The Octopus solver generated a range of structural configurations along a Pareto Front, presenting a trade-off between structural mass and structural displacement. Four key optimal solutions were extracted for evaluation:

- **Solution 1:** Achieved a displacement of 13.7 cm with a total mass of 1.6 x 10^6 kg.
- **Solution 2:** Achieved a displacement of 12.16 cm with a total mass of 2.0 x10^6 kg.
- **Solution 3:** Achieved a higher displacement of 52.8 cm but maintained a lower mass of 1.6 x10^6 kg.
- **Solution 4:** Achieved the lowest displacement of 2.9 cm but resulted in the highest mass of 2.6 x10^6 kg.

These variations highlight the necessity of clearly identifying and bounding variables prior to running generative models, as different spatial arrangements significantly impact structural performance metrics.

5. CONCLUSION:

Topology optimization provides maximum freedom in the design process by determining the optimal distribution of material without the constraints of an initial rigid structure. Real-time FEA plug-ins embedded in parametric environments allow for effective analysis during the early design phases. However, because long-span gridshell structures contain thousands of possible variations, the precise identification and bounding of variables prior to modeling are critical to prevent excessive computational time and ensure accurate optimization outcomes.

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