A Critical Review on Sustainable Structural Optimization using Computational Approach

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Abstract

Artificial Intelligence (AI) integration is bringing about a revolutionary change in the field of civil engineering. Artificial Intelligence (AI) methods like natural language processing, machine learning, and neural networks are being used to improve decision-making in civil engineering projects. AI algorithms help engineers create optimal structural designs throughout the design phase by taking a variety of aspects into account, such as cost limits, environmental circumstances, and material qualities. By automating tedious jobs and continuously monitoring site conditions, AI-driven robotics and autonomous machines during construction contribute to enhanced efficiency and safety. Structural optimization based on computational techniques has become one of the most widely utilizedapproaches for the sustainable and effective design in the field of civil engineering with the introduction and development of computational tools and information technology. Seismic events pose significant threats to the safety and stability of built environments, necessitating the development of robust structural designs capable of withstanding and minimizing the impact of such events.

The primary objective of the paper is to analyze research for sustainable structural optimization, to present an in- depth analysis of the optimization objectives and their temporal and spatial trends, to describe the optimization process, and to overcome the current research limitations and recommendation for future work. The significance of sustainability and efficiency in the sector are well introduced in the paper by consolidating and synthesizing existing knowledge in the field. This research paper provides valuable insights into the optimization of structural designs for seismic impact and taking into consideration of environmental sustainability.

Keywords

Artificial Intelligence, Structural Optimization, Energy Efficiency, Strength, Structural Reliability, Sustainable Design

1. Introduction

Artificial Intelligence (AI) in civil engineering is a paradigm change towards intelligent, flexible, and sustainable infrastructure. The use of AI technologies in civil engineering will surely change the field as they develop, encouraging innovation and enhancing the overall resilience and functionality of infrastructure systems. Artificial Intelligence systems are able to take into consideration the life cycle of materials, which helps choose environmentally favourable solutions and reduces the overall carbon footprint of buildings. AI-powered computational techniques aid in the creation of structurally sound designs. Buildings and infrastructure can become more resilient to natural catastrophes and climate change by enhancing structural safety through the use of machine learning models that analyse historical data, weather patterns, and other factors. AI-powered sustainable structural optimization enables flexibility in response to shifting circumstances. Structures may adapt dynamically to changes in their surroundings thanks to real-time data analysis, which guarantees their sustainability and continuous efficiency throughout time.

Structural optimization is one of the methods of optimization that is most frequently utilized. In this study, "structural optimization" refers to an optimization that ignores the properties of chosen materials in order to discover the best configuration of structures or structural components to meet specific goals under predetermined conditions. Early structural optimization research in the realm of civil engineering consists solely of programming techniques and mathematical theorems using simple structures as benchmarks.

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2. Methodology

The behavior of soil during an earthquake plays a significant role in determining the response of structures. Soil properties, such as stiffness, strength, and damping, can significantly influence the dynamic behavior of the foundation and affect the overall structural performance. Structural optimization approaches aim to improve the seismic performance of structures by considering soil-structure interaction effects.

To perform structural optimization based on soil behavior under earthquake impact, engineers often use advanced computational methods. Finite element analysis (FEA) and other numerical techniques can simulate the dynamic behavior of the soil-structure system and evaluate different design alternatives. Optimization algorithms are then employed to search for the most efficient and reliable design solutions based on predefined performance criteria, such as minimizing structural damage or maximizing structural robustness.

Moreover, probabilistic approaches can be applied to consider the uncertainties associated with soil behavior and earthquake loading. By incorporating probabilistic methods, engineers can account for the inherent variability and assess the reliability of the optimized designs.

3. Literature Review

As per, Bendsoe et al. [1] in this context the "lay-out" of the structure includes information on the topology, shape and sizing of the structure and the material distribution method allows for addressing all three problems simultaneously. Sizing, shape, and topology optimization problems address different aspects of the structural design problem. As per Rozvany et al. [8] conference proceedings; M. Balachandran et al. in structural optimization, computer- based systems have been used to assist in the numerical aspects of the optimization process. However, structural optimization involves a number of tasks which require human expertise and are traditionally assisted by human designers. These include design optimization formulation, problem recognition and the selection of appropriate algorithm(s). As per Huang et al. [4] demonstrate that the evolutionary structural optimization method is an effective approach capable of solving a wide range of topology optimization problems, including structures with geometrical and material nonlinearities, energy absorbing devices, periodical structures, bridges and buildings. In the study conducted by Roose, T., et al. [7] which focuses on the role of soil structure in nutrient and water management within agricultural systems. It explores how soil structure influences root development, nutrient availability, and water movement in the soil. The study suggests that optimizing soil structure through practices like reduced tillage, cover cropping, and organic amendments can enhance nutrient and water use efficiency in agroecosystems. As per study by Guest et al. [5] in discretized topology optimization issues, a method for imposing a minimum length scale on structural elements is described. In order to obtain the element volume fractions that conventionally characterise topology, nodal variables are implemented as the design variables and projected onto element space. Through mesh-independent functions built on the minimal length scale, the projection is made. Also one more study by Six, J., et al. [10] which examines the interrelationships between soil structure, organic matter content, and aggregate stability. It emphasizes the role of organic matter in promoting soil aggregation and stability, which in turn affects soil porosity, water infiltration, and nutrient availability. The study suggests that managing organic matter inputs can enhance soil structure optimization and improve overall soil health. As per study by Helio Henrique Soares Franco et al. [2] put forth the hypothesis that Visual Evaluation of Soil Structure (VESS) is sensitive enough to distinguish between structural quality (Sq) scores of VESS from soils with various textural classes that have been subjected to various management and cultivation practices under various climatic conditions. An extensive systematic review and meta-analysis of all indexed scientific papers that used the approach were compiled and examined in order to evaluate this claim. As per the paper by Long Jiang et al. [6] a double-well potential function is used for distance regularization inside the topology optimization loop. This functional can maintain the level set function's flatness in the remaining portion of the computational domain while enforcing the level set function's signed distance property in a restricted band along the design boundaries. As per the study by Hesaneh Kazemi et al. [3] the computational approach for designing architected truss lattice materials is presented in this study, and each strut can be formed of any of a variety of materials. To maximize effective properties, we design the lattices. As per the research by Sahar et al. [9] it has become more and more usual to use optimization algorithms in SHM systems, including their usage for OSP to arrive at an ideal solution. As a result, sophisticated approaches designed exclusively for SHM have been developed. This article also demonstrates the speed and efficiency with which these sophisticated artificial intelligence (AI)-based solutions may address challenging problems.

Singh, D., & Srivastava, D. found that without taking damper into account, a very high story displacement was discovered in the seismically active area. The building's structure improved and the maximum storey displacement was decreased to a minimal value with the installation of specific dampers, making the structure relatively safe.[11]

Emmanuel Kwame Nti et al. identified three crucial approaches to managing water pollution in relation to six significant facets of cutting-edge technology and artificial intelligence (AI). In order to efficiently remove pollutants from impacted water bodies, artificial intelligence (AI)-based decision-making systems optimise the use of diverse treatment technologies, including adsorption, ion exchanges, electrokinetic processes, chemical precipitation, phytobial remediation, and membrane technology. Additionally, attention was paid to the benefits and drawbacks of a number of cutting-edge technologies, the difficulties in utilizing them while recognizing their shortcomings, and potential technological roadmaps. By utilizing AI and other cutting-edge technology to address the current water pollution crisis and guarantee a sustainable and secure water supply for future generations, this effort contributes to the problems with water quality in Ghana's Pra river basin.[12]

The goal of the Pavitar Singh et al. study is to determine the ideal amount of fine LD slag replacement for fine aggregates. By volume, the slag took the place of fine aggregates at 25, 50, 75, and 100%. This paper presents the results of an investigation into how the use of LD slag affected the mechanical behaviour, durability, and microstructure of concrete. Moreover, the compressive strength of concrete was estimated using artificial intelligence (AI) techniques such Artificial Neural Networks (ANNs), Decision Trees (DT), and Random Forests (RF) utilising a total of 180 experimental data points. To evaluate the effectiveness of the created models, the coefficient of determination (R2), mean absolute error (MAE), and root mean square error (RMSE) were calculated.[13]

4. Objectives of Structural Optimization

1. **Minimize Weight**: Keeping a structure's strength and performance criteria while minimising its weight is one of the fundamental goals of structural optimization. This is crucial for sectors like aerospace and automotive where weight reduction can boost fuel economy, increase cargo capacity, or improve performance all around.
2. **Maximize Strength and Stiffness**: Increasing the structure's strength and stiffness is another goal of structural optimization. The load-carrying capacity can be increased and deformations can be decreased by optimising the design, guaranteeing that the structure can withstand applied forces and keep its integrity.
3. **Enhance Structural Performance**: The goal of structural optimization is to increase a structure's overall performance, which can include things like minimising deflections, raising natural frequencies, strengthening stability, increasing durability, and lowering vibrations. Engineers can modify the structure to fulfil particular performance needs by optimising the design.
4. **Minimize Cost**: Cost reduction is frequently a major goal in structural design. While retaining the necessary performance and safety requirements, production and maintenance costs can be decreased by optimising the design, material utilisation, and manufacturing processes.
5. **Improve Energy Efficiency**: Cost reduction is frequently a major goal in structural design. While retaining the necessary performance and safety requirements, production and maintenance costs can be decreased by optimising the design, material utilisation, and

manufacturing processes.

6. **Optimize Structural Reliability**: A structure's reliability and robustness can be improved by structural optimization. Designing the structure to be more resilient to these uncertainties entails taking into account elements like load changes, uncertainty in material qualities, or potential failure modes.
7. **Incorporate Design Constraints**: Various design limitations imposed by codes, standards, regulations, and functional requirements are addressed by structural optimization. Space restrictions, geometric restrictions, material restrictions, fabrication restrictions, and specialised safety rules are only a few examples of these limitations.

5. Objectives of Computational Approach in Structural Optimization

Computational approach towards sustainable structural optimization involves using advanced computer-based methods to design and optimize structures that are not only safe and functional but also environmentally friendly and resource-efficient. This approach aims to strike a balance between structural performance, cost-effectiveness, and environmental impact. Here are the key steps and components involved in such an approach:

a. **Problem Formulation:** Formulate the optimization issue by taking into account a variety of goals, such as minimising the number of materials used, cutting back on energy use during building and operation, maximising structural effectiveness, and assuring safety.

b. **Modeling and Simulation**: Utilising FEA or other pertinent simulation tools, create precise computational models of the structure. These models aid in predicting how the structure would behave under various loading scenarios.

c. **Multi-Objective Optimization:** Make use of optimization methods that can deal with numerous competing goals. To find the best solutions in the multi-dimensional design space, one can use surrogate-assisted optimization, gradient-based techniques, or evolutionary algorithms (such as genetic algorithms).

d. **Design Variables**: Define the design parameters that affect structural durability and performance. These could consist of different material types, cross-sectional size, connecting information, and more. Engineering, environmental, and financial factors should all be taken into account when putting restrictions and limits on each design variable.

e. **Objective Functions**: Create objective functions that measure the sustainability and structural performance metrics. The structural strength, stiffness, resilience to external forces, carbon footprint, embodied energy, and life-cycle cost, for instance, could all be measured by these functions.

f. **Environmental Impact Assessment**: Utilise life-cycle assessment (LCA) techniques to analyse the environmental impact of various design options. LCA takes into account the complete structure's life cycle, including raw material extraction, production, transportation, building, operation, upkeep, and disposal at the end of its useful life.

g. **Material Selection**: Utilise databases or tools that offer details about how various materials affect the environment, including information on embodied carbon, energy content, recyclability, and availability. Making knowledgeable selections concerning the choice of materials is aided by this.

h. **Constraint Handling**: Include restrictions relating to construction codes, environmental laws, and structural safety. For instance, make that the design complies with pertinent load and safety criteria while reducing any unfavourable environmental effects.

i. **Uncertainty and Sensitivity Analysis**: Consider the possibility that material qualities, loading conditions, and other factors could change. Conduct sensitivity analysis to determine how changes in the input variables impact the outcomes of the optimization.

j. **Validation and Testing:** Verify the optimised design is safe and performs as expected under realistic conditions by conducting physical tests or additional simulations.

k. **Continuous Improvement**: Consider real-world performance input, and track the structure's performance over time. Future designs will continue to be improved as a result of this feedback cycle.

6. Future Scope

i. **Sustainable Design**: Various design limitations imposed by codes, standards, regulations, and functional requirements are addressed by structural optimization. Space restrictions, geometric restrictions, material restrictions, fabrication restrictions, and specialised safety rules are only a few examples of these limitations.

ii. **Multidisciplinary Optimization**: Develop integrated optimization frameworks by combining many disciplines, such as structural, thermal, fluid dynamics, and material science. As a result, structures may be designed that are not only structurally sound but also effective in a range of operational circumstances.

iii. **Topology Optimization**: Improve current topology optimization methods to take into account more design restrictions, such as those imposed by manufacturing, fatigue life, and vibration control. This can aid in creating structural designs that are ideal in terms of weight, fabrication ease, and durability.

iv. **Advanced Materials**: Look into the usage of cutting-edge materials for structural optimization, such as composites, nanomaterials, and smart materials. Investigate their distinctive characteristics and behaviours to create optimized designs that take advantage of their advantages, such as a higher strength-to-weight ratio, increased durability, and improved energy absorption.

v. **Robust Optimization:** Create optimization techniques that take loading circumstances, material characteristics, and other design elements into account. Robust optimization tries to provide more dependable and robust designs by creating structures that can function well even in the presence of uncertainty.

vi. **Environmental Impact Assessment [Life Cycle Assessment (LCA)]:** Artificial Intelligence facilitates comprehensive assessments of the environmental impact of construction projects by considering the entire life cycle of materials and structures.

7. Conclusions

In a variety of disciplines, including civil engineering, aeronautical engineering, and mechanical engineering, the study of structural optimization has grown in significance. We can increase the performance, efficiency, and dependability of engineering systems while lowering costs and material utilization by optimizing the structural design.

From sizing and shape optimization to topology optimization and material selection, we looked into several structural optimization issues. We looked at the difficulties that come with each sort of problem and talked about cutting-edge solutions. We also talked about how to combine optimization with other design factors including sustainability, multi-objective optimization, and uncertainty analysis.

In conclusion, the combination of a computational strategy with sustainable structural optimization has enormous potential for influencing the development of a future in engineering and construction that is both ecologically responsible and effective. Engineers may design structures that excel in both performance and sustainability by combining sophisticated simulation techniques with multi-objective optimization algorithms. By using this method, structures can be designed to use the least amount of resources, energy, and environmental effect while still fulfilling safety and functional standards.

The computational method is a potent tool that engineers can use to help create a constructed environment that is more resilient and ecologically conscious in the goal of sustainability. This strategy will surely be essential in resolving the complicated problems of striking a balance between structural performance, economic viability, and environmental stewardship as technology develops further. We may open the door to a future in structural design and construction that is greener and more sustainable by adopting this technology.

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