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REVIEW

Applications of Artificial Intelligence in Structural Design in Civil Engineering

Aplicaciones de la Inteligencia Artificial en el Diseño Estructural en Ingeniería Civil

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ABSTRACT

Artificial intelligence (AI) is transforming the structural design paradigm in civil engineering. This article critically analyzes its applications, demonstrating that methods such as machine learning, neural networks, and genetic algorithms enable design optimization by overcoming the limitations of traditional approaches. AI tools facilitate the exploration of thousands of alternatives, multi-objective optimization (balancing cost, safety, and sustainability), and the automation of routine tasks, resulting in significant gains in efficiency, accuracy, and innovation. However, widespread adoption faces challenges such as dependence on quality data, model interpretability ("black box"), and the need for regulatory and professional adaptation. It is concluded that AI does not replace, but rather enhances, the work of engineers. The synergy between human judgment and these tools will be key to developing more efficient, resilient, and sustainable structures in the future, marking a turning point in the practice of structural engineering.

Keywords: Structural Design; Artificial Intelligence; Civil Engineering.

RESUMEN

La inteligencia artificial (IA) está transformando el paradigma del diseño estructural en ingeniería civil. Este artículo analiza críticamente sus aplicaciones, demostrando que métodos como el aprendizaje automático, las redes neuronales y los algoritmos genéticos permiten optimizar diseños superando las limitaciones de los enfoques tradicionales. Las herramientas de IA facilitan la exploración de miles de alternativas, la optimización multiobjetivo (equilibrando costo, seguridad y sostenibilidad) y la automatización de tareas rutinarias, lo que se traduce en ganancias significativas de eficiencia, precisión e innovación. No obstante, la adopción generalizada enfrenta desafíos como la dependencia de datos de calidad, la interpretabilidad de los modelos ("caja negra") y la necesidad de adaptación normativa y profesional. Se concluye que la IA no reemplaza, sino que potencia la labor del ingeniero. La sinergia entre el criterio humano y estas herramientas será clave para desarrollar estructuras más eficientes, resilientes y sostenibles en el futuro, marcando un punto de inflexión en la práctica de la ingeniería estructural.

Palabras clave: Diseño de Estructuras; Inteligencia Artificial; Ingeniería Civil.

INTRODUCTION

Structural design in civil engineering is a fundamental pillar of developing safe, functional,

and sustainable infrastructure. This process involves the complex integration of mechanical principles, technical standards, economic constraints, and environmental considerations. Traditionally, engineers have relied on the finite element method (FEM) and iterative procedures guided by regulations to achieve viable design solutions. While these methods are robust, they are often computationally expensive. They may be limited in their ability to exhaustively explore the vast space of possible solutions, especially in multi-objective optimization problems.

In this context, Artificial Intelligence (AI) emerges as a transformative paradigm, offering tools that complement and enhance engineers' capabilities. Machine learning (ML) and deep learning (DL) techniques can identify complex patterns and nonlinear relationships in large volumes of data, often surpassing the predictive accuracy of simpler analytical models.[1,2] This capability allows not only the automation of routine tasks, but also the discovery of novel and efficient structural configurations that might go unnoticed with conventional approaches.[3]

Despite its potential, the adoption of AI at the core of the structural design process has been slower compared to its application in areas such as structural health monitoring or failure prediction. Historically, applications have focused on the diagnostic and evaluation phase, leaving a significant gap in their integration during the conceptual and sizing phase. However, recent research is beginning to demonstrate the success of AI algorithms in key design tasks, such as predicting the mechanical properties of materials, performing topological optimization, and automatically dimensioning elements, promising significant reductions in time and effort.[4]

This article aims to provide a comprehensive review of the state of the art in AI applied to civil structural design. To this end, it will critically analyze the most relevant AI methods (e.g., artificial neural networks, genetic algorithms, support vector machines), present emblematic use cases in the literature, discuss the available computational tools, and finally contrast the benefits with traditional methods, without omitting a discussion of the limitations and future challenges facing this rapidly evolving discipline.

DEVELOPMENT

AI methods are commonly used in structural design

Structural design incorporates various AI methodologies to complement conventional approaches. The most relevant ones are described below.

Machine Learning

Machine learning (ML) uses algorithms that, based on historical data, make predictions or decisions without explicit programming. In the structural field, its main application is the creation of surrogate *models*. These metamodels approximate the results of complex analyses (such as finite element analyses) at a significantly lower computational cost, allowing thousands of design alternatives to be evaluated quickly and structural responses (loads, deformations) to be predicted with sufficient accuracy to speed up project iterations.[1]

Artificial Neural Networks (ANN)

Inspired by the human brain, ANNs are ML systems capable of recognizing complex patterns. They are trained with databases of structures or simulations to predict design parameters, such as the strength of elements or the dimensions of beams and columns. Advances such as deep and convolutional neural networks (CNN) enable more sophisticated applications; for example, analyzing architectural plans as images to predict the need for structural components before detailed modeling.[5]

Genetic Algorithms and Evolutionary Optimization

These techniques, inspired by natural selection, seek optimal solutions through iterations. They represent designs as "individuals" in a population, applying operators such as crossover

and mutation to "evolve" towards more efficient configurations. They are particularly useful for multi-objective optimization, balancing criteria such as cost, weight, and seismic performance, and finding non-intuitive solutions in complex systems.[6]

Generative Design

This automated approach uses algorithms (often combining ML and heuristic search) to generate multiple design alternatives that meet defined objectives (e.g., minimizing material use) under given constraints (e.g., loads, regulations).(1) It represents a paradigm shift: the engineer defines the problem and the AI generates a range of viable and, in many cases, innovative solutions, accelerating the conceptual phase.[1]

In addition to the above, other AI techniques are applied in niche areas of structural design. Rule-based expert systems were pioneers in past decades, codifying the knowledge of veteran engineers to advise on design decisions (e.g., standard rules incorporated into software). Fuzzy logic, meanwhile, has been used to handle uncertainty in design parameters and to characterize structural behavior in linguistic terms (e.g., "very safe," "not very flexible," etc.).[7,8,9]

Likewise, computer vision techniques enable the interpretation of visual data relevant to design, such as extracting geometry from scanned plans or evaluating the quality of structural details from photos. Even natural language processing (NLP) is beginning to find its place, with research focused on analyzing construction code texts or technical reports to integrate them into the automated design process. Although these complementary methodologies are less common than those mentioned above, together they demonstrate the broad spectrum of AI tools that can support the structural engineer.[10,11]

AI tools and software for structural design

The current software ecosystem includes various AI-based tools that specifically optimize stages of structural design. Some of the most relevant ones are highlighted below:

- *Daisy:* Uses genetic programming to generate and optimize wooden structure designs. It evaluates millions of configurations in minutes, reporting cost reductions of up to 10% through automated element design.[12]
- *Pathw.ai:* Platform that automates the design of steel connections through pattern recognition and continuous learning. It streamlines the process by reusing validated solutions and reducing errors in repetitive calculations.[13]
- *Structure Plus:* Cloud application that integrates with modeling software (ETABS, SAP2000) to optimize steel and concrete designs. It uses parallel processing to evaluate multiple scenarios simultaneously, minimizing material usage.[14]
- *Hypar + SkyCiv:* A generative design platform that combines parametric modeling with real-time structural analysis. It allows rapid iterations in the browser, facilitating comparisons of alternatives and early cost estimates.[15]
- *Asterisk (Thornton Tomasetti):* Functions as an ML-based virtual advisor, generating and comparing multiple structural options according to user-defined metrics (cost, efficiency). Integrates with BIM environments (Revit/Grasshopper) to refine designs.[16]

These tools demonstrate AI's ability to streamline specific processes, from element sizing to comprehensive optimization, offering tangible gains in efficiency and accuracy.

Practical Application Cases and Case Studies

Research into AI applied to structural design has yielded promising results that are now being implemented in real projects. The following cases illustrate its potential:

Seismic Pre-dimensioning with RNA (Mexico)

Researchers developed a neural network model trained with data from existing concrete buildings. The system predicts the dimensions of structural elements (columns, walls) based on height and soil type, achieving a maximum variation of 15% compared to traditional regulatory methods. This validates its usefulness in streamlining the preliminary design stages.[17]

Multi-objective optimization with genetic algorithms:

A study applied genetic algorithms to optimize cost and seismic performance in concrete buildings simultaneously. The methodology generated a Pareto front of optimal solutions, providing engineers with multiple balanced alternatives for decision-making.[18]

Architecture-Engineering Integration with Deep Learning:

A project at the University of Chile used deep neural networks and CNN to analyze architectural plans. The system predicts wall dimensions and suggests structural reinforcements directly from the conceptual stage, reducing iterations between disciplines and showing high correlation with final designs.[19]

Generative Design in Professional Practice (WSP/Autodesk):

A case study implemented generative design flows in real projects, demonstrating the ability to evaluate dozens of structural alternatives quickly. This enabled sustainability criteria to be incorporated from the early stages and to optimize collaboration between architects and engineers.[20]

These cases demonstrate how AI is transforming established practices, offering tangible improvements in efficiency, optimization, and interdisciplinary integration.

Benefits of AI over traditional methods

The integration of artificial intelligence into structural design offers substantial advantages over conventional approaches:

Expanded Exploration of Design Space

AI tools enable evaluating thousands of structural configurations in a short time, overcoming the limitations of manual analysis.[1] Generative design algorithms identify innovative and efficient solutions that balance multiple performance variables, expanding creative possibilities in the conceptual phase.[21,22]

Integrated Multi-Objective Optimization

Unlike traditional sequential methods, AI enables the simultaneous optimization of conflicting criteria such as cost, weight, and seismic safety.[1] This capability leads to better-balanced designs and often achieves significant reductions in material usage without compromising structural performance.

Increased Speed and Productivity

Automating repetitive tasks (pre-dimensioning, regulatory verification) shortens design cycles from days to minutes.[22,23] This efficiency frees engineers to focus on higher-value activities, improving the overall productivity of the design process.

Greater Accuracy and Informed Decisions

Models trained with large volumes of data provide more accurate predictions than traditional empirical formulas.[1] In addition, AI tools offer advanced visualizations and comparative analyses

that provide a better basis for technical decisions.[23]

Promoting Innovation and Sustainability

AI enables the design of unconventional geometries that optimize resource use, resulting in lighter structures with less environmental impact.[4,23] This capability positions AI as a key enabler for more sustainable structural engineering.[6,20]

Taken together, these advantages demonstrate the value of AI as a complement to engineers' expertise, particularly on increasingly complex projects where traditional methods are insufficient.

Current limitations and challenges

Data Availability and Quality

AI models, particularly deep learning models, require large volumes of training data. In civil engineering, structural data is often scarce, fragmented, or restricted in access.[1,23] The compilation of representative datasets is complicated by the typological diversity of structures, which can limit the generalization of models. Progress requires coordinated efforts in standardization and data sharing at the sectoral level.

Interpretive Complexity ("Black Box")

Techniques such as deep neural networks operate as systems that are difficult to interpret, generating understandable mistrust in a field where traceability is crucial.[1,22] The inability to justify specific recommendations (such as reducing a structural section) slows adoption. Research into explainable AI (XAI) seeks to mitigate this problem, but it currently remains a significant practical obstacle.

Regulatory Compliance and Construction Feasibility

Ensuring that AI-generated solutions comply with building regulations and are constructively viable poses a considerable challenge.[1] Algorithms may propose mathematical optimizations that violate specific regulatory provisions or prove impractical.[24] Expert human validation, therefore, remains indispensable, adding a necessary layer of control to the process.

Cultural Resistance and Training Gap

The introduction of AI is met with skepticism among professionals trained in traditional methods.[1] There are well-founded fears about the loss of professional control and the possible devaluation of expertise. Overcoming this barrier requires demonstrating reliability through success stories and developing training programs that integrate structural engineering and data science knowledge.[25]

Ethical and Legal Liability Issues

The attribution of responsibility in the event of failures and possible biases in training data poses ethical and legal challenges.[1,26] Ultimate responsibility currently lies with the signing engineer, but more specific regulatory frameworks are needed to address the growing autonomy of these systems.

Progressively overcoming these limitations will be essential to consolidating AI's role as a reliable tool in the professional practice of structural design.

CONCLUSIONS

Artificial intelligence is a transformative tool for structural design, enabling optimization of processes, increased accuracy, and the exploration of innovative solutions that exceed the limits of traditional methods. Its integration enables multiple objectives, such as efficiency, safety,

and sustainability, to be addressed simultaneously. However, AI complements—not replaces—engineering expertise. Human validation remains crucial to ensure regulatory compliance and construction feasibility. Once current technical and methodological barriers are overcome, progressive adoption is expected to enhance engineers' capabilities. The future of structural design will be based on the synergy between artificial intelligence and professional judgment, geared toward more efficient, safer, and sustainable structures. This collaboration will enable new standards of excellence in structural engineering to be achieved.

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