

Research Article

Research and Practical Reform on the Practical Teaching of Structural Mechanics Courses Empowered by AI Under the Background of Carbon Peaking and Carbon Neutrality

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Abstract

With the advancement of the 'dual carbon' strategy, fundamental changes are occurring in the curriculum and pedagogy of Structural Mechanics. Empowered by artificial intelligence (AI), this shift has not only revolutionized traditional instructional models but also redefined the essence of engineering talent development. This paper investigates the pedagogical transformation of structural mechanics education, specifically focusing on: (1) the cultivation of design thinking from "mechanical analysis" to "green intelligent design"; (2) the construction of an intelligent learning paradigm through the deep integration of "physical mechanisms, virtual simulation, and AI prediction"; (3) the development of an interdisciplinary, modular knowledge system combining "Mechanics, AI, and Carbon Management"; and (4) the establishment of a multidimensional, process-oriented learning evaluation system driven by AI data analytics. Going forward, structural mechanics education will place greater emphasis on ability-oriented practical teaching. It should adhere to the guiding principle of "technology empowerment with education as the foundation," ensuring that AI serves as a tool to enhance-rather than replace-the core values of traditional pedagogy. Educators must therefore strike a careful balance between embracing technological innovation and preserving educational heritage. This study takes mindset reshaping as its core innovation, aiming to cultivate interdisciplinary professionals who can effectively apply AI tools, uphold low-carbon concepts, and solve complex engineering challenges creatively. It is not only a teaching reform practice but also a forward-looking exploration for the future development of engineering education.

Keywords

AI, Structural Mechanics, Practical Reform, Carbon Peaking and Carbon Neutrality

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Received: 20 January 2026; **Accepted:** 14 February 2026; **Published:** 27 February 2026



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1. Introduction

Chinese universities are currently deepening the integration of AI technology into structural mechanics curricula. Driven by big data technology and high-performance computing, artificial intelligence methods such as deep learning and reinforcement learning have not only restructured the technical pathways of structural mechanics analysis, but also enabled paradigm innovations in key fields including cross-scale modeling and real-time response prediction [1]. Similarly, the Department of Energy and Power Engineering at Tianjin University has established a novel curriculum system supported by "three major pillars"-mathematical sciences, mechanics and thermal-fluid sciences, and intelligent & computational sciences-guided by the construction philosophy of "one line, two drivers; three foundations in synergy; strengthening fundamentals with interdisciplinary approaches; and integrated practice" [2]. The "dual-engine" teaching model combining virtual and physical elements has become a defining feature of AI-empowered structural mechanics education. This model enables students to complete material R&D processes-which traditionally take months-through virtual experiments. Additionally, it utilizes big data analytics to monitor student learning behaviors in real-time and provide personalized learning pathways [3, 4]. Industry-education integration serves as a crucial safeguard for AI-empowered structural mechanics education. The 2025 International Conference on Engineering Education Development emphasized advancing the "New Engineering 2.0" initiative, which involves establishing a number of industry-university collaborative platforms with engineering characteristics and developing a batch of smart classrooms and intelligent learning practice bases [2, 6]. This strategic direction will further strengthen the role of industry-education integration in structural mechanics teaching.

Internationally, universities are placing greater emphasis on the design of personalized learning pathways in AI-empowered structural mechanics education [7]. The principles articulated by Lincoln in the Gettysburg Address have been extended to establish a new paradigm in mechanics education, characterized by "human-in-the-loop", "dual-brain construction", and "embodied intelligence" [4]. Intelligent tutoring systems have been widely used in universities across Europe and America. These systems are capable of automatically adjusting teaching content and difficulty levels based on students' learning progress and comprehension, providing immediate feedback and guidance. Furthermore, a progressive learning process-comprising "theoretical modeling, virtual simulation, and physical verification"-is facilitated through virtual simulation platforms [4, 5]. This approach allows students to experiment, fail, and learn from mistakes in a safe environment, thereby gradually cultivating their ability to solve complex engineering problems.

Against the backdrop of the "Dual Carbon" strategy, AI-empowered structural mechanics education is undergoing a phase of rapid development [6]. Universities worldwide are

actively advancing pedagogical innovations through curriculum reconstruction, the integration of virtual and physical teaching models, and industry-education collaboration. Looking ahead, with the deeper application of technologies such as knowledge graphs, digital textbooks, and competency-oriented practices, structural mechanics instruction will become increasingly personalized, intelligent, and practical. To address challenges related to faculty transformation, data security, and technological balance, it is essential for universities, enterprises, and society to work collaboratively. This synergy will drive the high-quality development of structural mechanics education, thereby providing crucial talent support for achieving the Dual Carbon objectives.

2. Current Issues in the Structural Mechanics Curriculum

2.1. Disconnection from Engineering Frontiers and "Dual Carbon" Goals

Currently, the content of structural mechanics courses remains centered on classical mechanical theories established a century ago, lacking a systematic introduction to modern engineering methods essential for the industry, such as computational mechanics, intelligent simulation, and optimization design. Students become proficient in manually calculating statically determinate structures but remain ignorant of the principles and applications of finite element software widely used in the industry-this represents a severe imbalance between classical theory and modern methods. Course content rarely involves topics such as life-cycle assessment of structures, embodied carbon calculation, and energy-saving and emission-reduction design principles. Upon completing the course, students only know how to ensure structural safety but lack the knowledge to design structures that are "low-carbon" throughout the entire process of construction, operation, and demolition. This deficiency indicates a lack of "green" and "sustainable" connotations, resulting in a serious disconnection from the "Dual Carbon" strategy. Course cases are mostly based on traditional concrete and steel; the mechanical properties of green building materials such as composite materials, recycled materials, and timber structures are scarcely covered. The curriculum responds slowly to new materials and systems and provides insufficient discussion on the mechanical problems of emerging structural systems like prefabricated buildings and 3D-printed buildings.

2.2. Predominance of "Teacher-centered" and "Knowledge-imparting" Methods

The teacher acts as the single source of knowledge, keeping students in a passive receiving mode. For abstract concepts

such as internal forces and deformations in structural mechanics, the lack of interactive and visualized tools leads to difficulties in understanding, forcing students to rely on rote memorization of formulas and problem-solving patterns. Teaching often remains stuck on idealized models like simply supported beams and cantilever beams, resulting in weak connections to real, complex engineering backgrounds. Students do not know how force displacement methods or matrix displacement methods are applied in real super high-rise buildings or long-span bridges, leading to a lack of understanding of the practical application of their studies and insufficient motivation to learn. Under the current class-based teaching model, teachers cannot attend to the learning difficulties and pace of individual students. High-achieving students are "under-challenged," while struggling students "give up," leading to polarized teaching outcomes.

2.3. Misalignment with Digital and Intelligent Trends in Practice

Most existing experiments are designed to verify known theories (e.g., the normal stress formula for beam bending), featuring fixed procedures and expected results. Students follow step-by-step instructions, lacking training in the scientific inquiry skills of experiment design, problem identification, and data analysis. Experiments heavily rely on expensive physical equipment, while the application of virtual simulation experiments and digital twin technologies—which allow for parametric studies and low-cost trial-and-error—is insufficient. Students cannot conduct destructive experiments or simulations under complex environments, limiting their horizons. The recording and processing of experimental data still rely heavily on manual work; students have no opportunity to use tools like Python or MATLAB for data analysis and modeling, missing a chance to develop data science as a core competency.

2.4. Inability of Assessments to Measure Comprehensive Competence

The proportion of the final exam in the total grade is excessively high. The assessment focuses on calculation techniques and speed rather than the depth of understanding of mechanical concepts or the ability to solve practical engineering problems. It fails to effectively evaluate students' thinking, attempts, collaboration, and innovation during the learning process. To achieve high scores, students tend to practice repetitive problems and memorize solution templates rather than truly understanding and innovating. Assessment content rarely involves non-technical qualities related to the "Dual Carbon" goals, such as sustainable design concepts, engineering ethics, and multi-objective trade-off decision-making-qualities that are precisely the core qualities required of future engineers.

2.5. Lack of Organic Integration Across the Curriculum

Knowledge in structural mechanics is isolated from courses in materials science, architectural design, civil engineering construction, and project management, failing to integrate effectively. Consequently, students struggle to establish a systematic way of thinking that connects "mechanical analysis - material selection - architectural design - carbon emissions," leaving them unable to respond to complex, comprehensive engineering challenges.

3. Key Challenges and Countermeasures in the Reform of Structural Mechanics Education

Artificial intelligence technology is profoundly reshaping the field of education, and its application in instructional design has become a core driving force for the transformation of teaching models [8]. The implementation of AI-empowered pedagogical reform in structural mechanics, under the "Dual Carbon" strategy, will face challenges in five key areas: curriculum reconstruction, teaching methodology innovation, practical instruction upgrading, faculty development, and assessment system reform.

The core difficulty regarding curriculum reconstruction lies in the entrenched traditional knowledge system, which hinders the integration of new AI and "Dual Carbon" knowledge, coupled with a lack of high-quality interdisciplinary teaching cases. To address this, a dynamic linkage mechanism will be established between course content, industry standards, and research frontiers, through which AI and "Dual Carbon" elements will be modularly embedded.

Regarding pedagogical innovation, the core difficulties include inadequate AI application skills among faculty, students' potential over-reliance on AI for assignments, and the inability of traditional methods to meet new demands. To tackle these issues, a faculty AI literacy enhancement program will be implemented; assignment and assessment methods will be reformed to emphasize process evaluation and practical skills; and teaching models integrating virtual and physical elements will be promoted.

For the upgrading of practical teaching, the core difficulties involve high costs and long cycles of experimental equipment, the disconnection between AI simulation platforms and real engineering scenarios, and insufficient cultivation of students' abilities to solve complex engineering problems. To resolve these, a progressive system integrating "virtual simulation, physical experiments, and project-based practice" will be constructed; industry-education integration will be deepened; and real-world project cases from enterprises will be introduced.

In terms of faculty development, the core difficulties are the single-discipline knowledge structure of instructors and the lack of effective motivation and evaluation mechanisms. To

overcome these, interdisciplinary teaching teams will be formed, and AI application competence will be incorporated into faculty assessment and incentive systems.

Finally, regarding assessment system reform, the core difficulties are that traditional examinations are inadequate for evaluating AI application skills and innovative thinking, and that learning process data is difficult to collect and utilize. To address this, a multi-dimensional, process-oriented evaluation system will be constructed, leveraging AI technologies themselves to enable personalized learning assessment.

4. Main Research Content of Structural Mechanics Teaching Reform Under the "Dual Carbon" Background

Under the guidance of the "Dual Carbon" strategy, the deep integration of artificial intelligence (AI) into the pedagogical reform of structural mechanics courses is a pivotal measure for cultivating engineering talents in the new era. Artificial intelligence technology is reshaping industrial working models and talent demands, while traditional teaching models can hardly adapt to these changes [9]. The core of this reform lies in constructing a novel teaching paradigm that places "green thinking" at its soul and "intelligent technology" at its core infrastructure. This paper systematically investigates the reform from the reconstruction of curriculum content and knowledge systems, the innovation of teaching methodologies and models, the upgrading of practical training systems, the development of teaching resources and assessment frameworks and faculty development coupled with ethical considerations.

4.1. The Reconstruction of Curriculum Content and Knowledge Systems

The core objectives of this research focus are the integration of the "Dual Carbon" goals, industry case-driven instruction, and the embedding of frontier knowledge. The study primarily concentrates on the integrated teaching of mechanical properties of green materials, AI-assisted structural analysis and optimization and life-cycle carbon emission assessment. This research aim to place the "environmental attributes" of materials on an equal footing with their "mechanical attributes" in teaching, thereby cultivating students' awareness of sustainable material selection. The curriculum will introduce novel green materials, systematically presenting the mechanical properties of high-performance recycled aggregate concrete, bamboo-composite materials, and low-carbon cement. Furthermore, a "Performance-Carbon Footprint" correlation database will be established. Within the teaching process, students will be provided with or guided to query the carbon emission coefficients corresponding to the unit strength of different materials. The goal is to enable students to master AI not merely as a "powerful calculator" for obtaining analytical solutions, but as an "innovation engine" for rapidly seeking optimal solutions.

While traditional teaching focuses on the derivation of classical theoretical formulas and precise calculations of simple structures, this reform introduces user-friendly AI optimization tools or open-source libraries (e.g., Scikit-learn, TensorFlow in Python) for simple predictions. Large language models such as DeepSeek-R1 have shown advantages in lowering the threshold for computational structural mechanics research and improving the efficiency of algorithm development [10]. ChatGPT has also demonstrated outstanding performance in assisting with the programming of computational structural mechanics [11]. Students will utilize trained machine learning models to rapidly predict stresses and displacements in key structural parts based on geometry and loading, cross-validating these predictions with classical theoretical results. This approach integrates systems engineering thinking and sustainable development concepts into structural mechanics, fostering a holistic "cradle-to-grave" perspective among students. Students will first understand the dual "mechanical-environmental" attributes of available materials. They will then employ AI tools to conduct structural design with "carbon reduction" as one of the optimization objectives. Following this, they will perform a carbon audit on the optimized design to quantify its environmental benefits using data. Based on the evaluation results, students will reflect on the rationality of material selection or optimization parameters, iterating their designs accordingly. Ultimately, this restructuring ensures that students master not isolated, but a comprehensive methodology for addressing "Dual Carbon" challenges: how to leverage intelligent technologies to design modern structures that are safe, economical, and environmentally friendly. Through this evolution, the structural mechanics course transforms from a traditional disciplinary foundation course into a core platform course for cultivating future sustainable civil engineers.

4.2. The Innovation of Teaching Methodologies and Models

The core objectives of this research focus are student-centeredness, the integration of virtual and physical elements, and the resolution of practical engineering problems. The study primarily concentrates on intelligent teaching platforms and personalized learning paths, virtual simulation and digital twin pedagogy and project-based and case-driven instruction.

The three key technologies of artificial intelligence—intelligent recognition technology, learning analytics technology, and virtual reality technology—play an important role in education and teaching [12]. We aim to construct an intelligent, blended teaching model characterized by being "student-centered, data-driven, and green-oriented." It fosters students' awareness of sustainable development. It also develops their ability to solve complex engineering problems. Utilizing AI algorithms to analyze students' learning behavior data—including video viewing duration, interaction points, types of homework errors, and discussion forum posts—the system will dynamically assess their mastery of knowledge and learning

styles. Based on this analysis, it will recommend optimal learning sequences, learning materials with progressive difficulty, and targeted review strategies. This approach abandons the "one-size-fits-all" teaching pace, truly realizing personalized instruction. Developing or introducing a "Structural Mechanics-specific AI Teaching Assistant" based on large language models (LLMs). This assistant will provide all-day responses to student inquiries regarding concepts, formulas, and principles. Crucially, it will employ Socratic questioning to guide students toward deeper thinking rather than directly providing answers. Simultaneously, it will automatically grade conceptual and discursive assignments, thereby freeing up instructors' time for higher-value tasks. Centered on "Dual Carbon" objectives (such as lightweight design, green buildings, and structural health monitoring for lifespan extension), we will develop a series of highly interactive virtual simulation cases. For instance, students will adjust beam and column cross-sections and materials (including novel green materials), and the AI will instantly calculate and visualize the resulting changes in stress, strain, displacement, and carbon footprint. This tightly couples abstract mechanical concepts with concrete energy-saving and emission-reduction goals. Furthermore, project-based learning tasks will be designed to allow student groups to collaboratively complete a structural design scheme that minimizes carbon emissions while satisfying mechanical performance requirements, utilizing AI tools such as structural optimization algorithms and generative design software. In this process, AI acts as a "collaborative partner," providing data analysis, scheme generation, and multi-objective optimization suggestions. By means of intelligent teaching systems, automated assessment, ideological and political case presentation, and other approaches, artificial intelligence transforms software engineering classrooms into more flexible and interactive learning scenarios, thereby effectively improving teaching quality and effectiveness [13]. This methodology effectively cultivates students' teamwork and innovative design capabilities.

4.3. The Upgrading of Practical Training Systems

Breaking the constraints of time and space, aligning with authentic industrial demands, and enhancing comprehensive innovation capabilities are the core tenets of this research. We aim to construct a progressive system integrating "virtual simulation, physical experimentation, and project-based practice" to strengthen the industry-education integration platform. This method aims to get past the drawbacks of conventional experiments in terms of space, cost, and safety by establishing an intelligent experimental teaching system characterized by the integration of virtual and physical elements, digital twins, and data-driven methodologies. For typical experiments (e.g., tension/compression, bending, and column buckling), high-fidelity virtual simulations based on physics engines will be devel-

oped. Students can arbitrarily set parameters (materials, dimensions, boundary conditions) in a virtual environment to conduct experiments that would be costly, risky, or time-consuming in reality—such as destructive tests or long-term creep experiments—thereby gaining an intuitive understanding of mechanical phenomena. Corresponding digital twin models will be created for physical experimental equipment. Before conducting physical experiments, students will perform pre-operations on the digital twin to familiarize themselves with procedures and predict outcomes. During the physical experiment, sensor data will drive the digital twin in real-time, allowing for comparative analysis between the two. This enables students to deeply understand the discrepancies between models and reality. An experimental data post-processing platform integrated with AI algorithms will be developed. This platform will automatically process data collected from both physical and virtual experiments, intelligently identify material properties, and perform anomaly detection and reliability analysis. By automating these tasks, students' focus will be shifted from tedious data processing to the exploration of phenomena and underlying principles. Innovation experiments will be designed to address the "Dual Carbon" theme of extending structural lifespan and minimizing demolition and reconstruction. For instance, students might deploy sensor networks on a simply supported beam model and utilize AI algorithms to analyze collected vibration data for damage identification and localization. Through a modular curriculum system that integrates structural mechanics principles with "dual-carbon" themed design, and adopting a hybrid teaching mode of "flipped classroom + PBL (Project-Based Learning)", we strengthen the engineering practice orientation [14]. Such projects seamlessly integrate structural mechanics, sensor technology, data science, and the concept of sustainable development.

4.4. The Development of Teaching Resources and Assessment Frameworks

This section investigates the development of new-format digital teaching materials and knowledge graphs, as well as the introduction of AI-assisted, multi-dimensional learning assessment. Constructing a "Dynamic, Intelligent, and Contextualized" Exercise System, which is to transform the exercise bank from a static assessment tool into an active learning resource that fosters student capability development. Instead of viewing exercises as isolated units, we will construct a multi-dimensional knowledge graph that interconnects mechanical concepts, problem-solving strategies, engineering scenarios, and carbon emission factors. Designing open-ended exercises with no standard answers, requiring students to utilize AI tools to balance and optimize among multiple objectives, such as mechanical performance, construction cost, and embodied carbon. These exercises aim to cultivate students' complex engineering decision-making abilities in service of the "Dual Carbon" strategy.

4.5. Faculty Development Coupled with Ethical Considerations

In this framework, professional ethics serve as the soul, AI literacy and interdisciplinary competence constitute the hard power, ethical guidelines act as the code of conduct, and interdisciplinary teams function as the platform that aggregates all these strengths. In the teaching process, methods and practices integrating ideological and political education elements should be adopted, the spirit of craftsmanship should be incorporated, and an Internet plus ideological and political education model should be constructed [15]. Enhancing teachers' AI literacy and interdisciplinary competence is the technical foundation of this reform; educators must first possess the ability to master new knowledge and technologies. Conduct tiered and categorized training through "AI-Empowered Education" workshops. Content ranges from foundational Python data processing and machine learning concepts to advanced applications of structural optimization algorithms and development of AI teaching tools (e.g., virtual simulation platforms), catering to faculty with different starting points. Implement an "Interdisciplinary Visiting Program" to encourage and fund structural mechanics instructors to engage in short-term exchanges at computer science schools, environmental colleges, or cutting-edge enterprises, thereby breaking down knowledge silos. Establish "AI + Mechanics" teaching innovation studios. Led by campus pioneers, these studios will regularly hold collective lesson planning and case studies to concretely transform AI technology and "Dual Carbon" knowledge into teachable classroom modules. Establishing ethical guidelines for technology application provides the value orientation and safety barrier for the reform, ensuring that AI is used responsibly for the benefit of students and society. Formulate Guidelines for AI Application Ethics in Structural Mechanics, clearly defining the boundaries of AI tool usage. Regarding academic integrity, specify what constitutes acceptable AI assistance (e.g., in programming, design optimization) versus what constitutes academic misconduct (e.g., directly submitting AI-generated answers). For data privacy, mandate anonymization of student data used in teaching research to protect individual privacy. Emphasize critical thinking and the "explainability" of AI results. Students and teachers must not blindly trust AI outputs but must critically verify them against mechanical principles. Engineering Ethics: Integrate engineering ethics into case studies. In project-based learning, design scenarios where students discuss the ethical implications of technical solutions, such as the social risks of "pursuing carbon reduction at the expense of structural safety margins." Building interdisciplinary teams is essential, as no single-discipline instructor can independently undertake this reform. Establish a "1+1+N" structured team: 1 core mechanics instructor + 1 computer science/AI specialist + N experts from enterprises, materials science, or environmental fields (serving as a flexible think tank). Reconstruct the teaching evaluation and incentive system to fully recognize faculty

contributions to interdisciplinary teaching and performance appraisals, thereby providing institutional momentum for team building.

5. Conclusions

Against the strategic backdrop of "Dual Carbon" and the technological impetus of "AI empowerment," a fundamental transformation in structural mechanics education is imperative-spanning its philosophy, methodology, content, and paradigm.

Elevating the Pedagogical Vision: Teaching objectives must evolve from cultivating singular structural analysis skills to fostering an integrated decision-making capability focused on the "green, economic, and intelligent" lifecycle design. This represents a dimensional upgrade of educational goals, internalizing "Dual Carbon" values and "AI" methodologies as the core literacy of students, thus addressing the fundamental needs of our time.

Innovating the "How": We must break free from the linear model of "theoretical lectures + exercise sessions" and construct a three-dimensional teaching environment characterized by the integration of virtual and physical elements, human-computer interaction, and dynamic feedback. This shift transforms the learning model from "passive reception" to "active inquiry" and from "uniform instruction" to "personalized interaction," significantly enhancing learning immersion and teaching efficiency.

Innovating the "What": A systematic reconstruction of content is required to dismantle traditional disciplinary silos. We propose establishing a new interdisciplinary knowledge architecture where "Mechanics forms the foundation, AI serves as the application, and Dual Carbon objectives guide the framework."

Ensuring Reform Efficacy: Moving beyond the traditional "one-exam-decides-all" assessment model is crucial. Evaluation must shift from "knowledge testing" to "competency assessment," ensuring a more scientific, objective, and comprehensive process that provides real-time data support for pedagogical improvement.

The core innovation of this study is "Mindset Reshaping." Its goal is to develop interdisciplinary professionals capable of effectively utilizing AI tools, firmly adhering to low-carbon principles, and creatively addressing complex engineering challenges. This initiative goes beyond simple teaching reform; it embodies a progressive exploration into the future landscape of engineering education.

Author Contributions

Tianyu Li: Conceptualization, Funding acquisition, Project administration, Resources, Writing – review & editing

Lidan Mei: Data curation, Formal Analysis, Methodology, Writing – original draft

Enhua Cao: Investigation, Validation

Yu Rao: Investigation, Writing – original draft

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Funding

This work was supported by the Major Project of the 2025 Teaching Reform Project of Sanjiang University: Project No. J2025KP06; Jiangsu Association for Science and Technology (JAST) Young Talents Lift-up Program: Grant No. JSTJ-2025-708; General Program of the National Natural Science Foundation of China: Project No. 52478165; Youth Program of the Jiangsu Provincial Natural Science Foundation: Project No. BK20230955; Achievement of the Sanjiang University Scientific Research Funding Project: Project No. 2025SJKY003.

Conflicts of Interest

The author declares that there is no conflicts of interest regarding the publication of this article.

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