

Reconstruction of the "Tree-Chain-Layer" Teaching Paradigm of Mechanics of Materials from the Perspective of New Engineering and Classroom Innovation Practice

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Abstract: Under the background of new engineering, the traditional teaching model of Mechanics of Materials fails to meet the demand for high-level talents in emerging industries. The course's abstract content, complex formulas, and cross-scale stress-strain-failure logic cause poor student learning outcomes. To solve this, this paper reconstructs the "Tree-Chain-Layer" teaching paradigm by exploring content, mode, and practice. For content, a "Knowledge Tree" is built (with "external forces and constraints" as root, "cross-sectional geometric properties" as trunk, four basic deformations as main branches, and "energy method", "stability", etc., as top elements), threaded by the "external force-internal force-stress-deformation-failure" chain, and divided into three learning levels. This reform upgrades the course to a problem-driven, interdisciplinary engineering base. Future efforts will open classroom boundaries to serve emerging industries.

Keywords: Mechanics of Materials, New Engineering, "Tree-Chain-Layer" Teaching Paradigm.

1. Introduction

Mechanics of Materials is a discipline that investigates the strength, stiffness and stability of engineering components under external forces. It is a compulsory core course for students majoring in mechanical, civil, aerospace, materials and other fields after they have completed advanced mathematics, college physics and theoretical mechanics. This course lays a core theoretical foundation for students to engage in structural design, safety assessment and new material research and development in the future, and plays a key role in connecting the previous and subsequent courses in the professional training program.[1,2] However, due to the complex symbols and numerous formulas in the course, as well as the chain of stress-strain-failure spanning micro, meso and macro scales, students generally find it abstract and dull, resulting in poor learning outcomes. Under the background of new engineering, the traditional "teacher lectures - students calculate" model is no longer able to meet the demand of emerging industries such as intelligent manufacturing, commercial aerospace and flexible electronics for high-level talents who "can model, simulate, optimize and innovate". It is urgent to reconstruct the knowledge system and reshape the teaching paradigm to achieve an update in educational concepts and a leap in teaching quality, and to help graduates support and lead future industries.[2,3]

Based on the above requirements, this paper systematically explores three main lines-content, mode and practice-around the characteristics of Mechanics of Materials, to cultivate interdisciplinary, research-oriented and innovative talents.

2. Content and Characteristics of the Mechanics of Materials Course

Based on the continuum hypothesis, Mechanics of Materials studies the internal forces, stresses, deformations and failure laws of bars, shafts, beams, plates, shells and their

combinations under tension, compression, bending, torsion, shear and combined loads. The content runs through force analysis-internal-force calculation-stress-field description-strength criterion-stiffness verification-stability determination-fatigue and fracture assessment.[4] The course is highly interdisciplinary and presents pronounced difficulties: the stress-strain field involves multiple variables, and differential equations coexist with energy methods, demanding simultaneous command of vector analysis, tensor concepts and integral transformations-students are easily intimidated by the mathematical threshold; Simplifying real engineering components (variable cross-sections, anisotropy, complex loading) into solvable "beam-plate-shell" models requires accurate identification of dominant variables and reasonable assumptions, while novices often swing between "over-modeling" and "over-simplification"; The strength, stiffness and stability criteria frequently appear together and wax or wane with load type, material properties and boundary conditions, making it hard for students to develop an intuitive grasp of "when to apply which criterion"; The macro formulas must be coupled with microscopic damage, mesoscopic interfaces and macroscopic structural responses, as in the coupling between interlaminar shear and global buckling of composite laminates, requiring a cross-scale perspective from millimetres to metres-an aspect easily overlooked by traditional single-scale teaching.[5] The course combines rigorous theory, numerous formulas and direct engineering relevance, yet faces the practical dilemmas of obsolete cases, missing contexts and compressed hours. More critically, new materials (carbon nanotubes, graphene, shape-memory alloys) and new processes (3D printing, filament winding, flexible-electronics integration) render the traditional steel-aluminium-concrete framework insufficient to cover all engineering scenarios.[6] Consequently, a systematic pedagogical upgrade is imperative to synchronise course delivery with technological innovation.

3. Explorations in Teaching Reform of the Mechanics of Materials Course

3.1. Constructing a “Knowledge Tree” to Systematise the Structure

Using a “knowledge tree” as the framework, all contents of Wang Bo’s Mechanics of Materials are integrated bottom-up into a logically clear tree: the root is “external forces and constraints”, the trunk is “cross-sectional geometric properties”, four main branches correspond to the four basic deformations (axial tension/compression, torsion, shear and bending), side branches grow into “combined deformation”, the top blooms into the “energy method”, bears the fruit of “stability”, and finally sows the seeds of “fatigue and dynamic loads”. Each branch is further threaded by the four-chain sequence “external force-internal force-stress-deformation-failure”. For example, on the “bending” branch, students first write the shear-force and bending-moment equations along the external-force chain, then derive $\sigma = My/I$ along the stress chain, next obtain the deflection w along the deformation chain, and finally check against strength, stiffness and stability criteria along the failure chain. Learning depth is further stratified into three levels: Level 1 memorises symbols and formulas, Level 2 completes single-deformation modelling and solution, and Level 3 performs global optimisation of real components (e.g. wings) involving coupled tension–bending–torsion, thereby seeing both the forest and the trees.

Across all chapters of Mechanics of Materials, patterns can be discerned. The chain “external force-internal force-stress-deformation-failure” constitutes a self-consistent cognitive pathway. It begins with any mechanical or environmental load acting on a structure, which, through support reactions and cross-sectional equilibrium, is transformed into internal forces such as axial force, shear force, torque and bending moment. The distribution of these internal forces over the cross-section is depicted by the stress field, with normal and shear stresses jointly describing the state of stress at every material point. Through constitutive relations and geometric constraints, stresses induce measurable or calculable deformations—including axial elongation, sectional rotation or deflection. When deformation accumulates to a certain extent, a local region of the material or structure reaches critical thresholds of strength, stiffness or stability, triggering crack initiation, excessive displacement or global buckling and thus failure. The entire chain takes “external force” as its entry and “failure” as its exit; every link is both the inevitable extension of the preceding and the prerequisite of the succeeding, forming a closed-loop logic: only by accurately quantifying external forces can internal forces be correctly solved; only by precisely characterising the distribution of internal forces can a reliable stress field be obtained; only by truly grasping the stress field can the deformation process be predicted; only by coupling deformation with material properties, geometric boundaries and stability criteria can the safety of the structure be finally assessed. If students can fluently traverse this chain in any deformation mode, they can distil seemingly scattered formulas and cases into a transferable generic path, leaping from “being able to solve problems” to “being able to solve complex engineering problems”.

3.2. Telling Scientific Stories to Arouse Deep Interest

During the process of learning a large amount of professional knowledge, students often feel bored and uninterested. We can narrate the scientific stories behind natural laws and principles to stimulate interest and affection for the Mechanics of Materials. Throughout its long history, almost every breakthrough in the mechanics of materials has been accompanied by a gripping scientific story that reveals profound natural laws and maps the expansion of human cognition. The course team, in collaboration with enterprises in aerospace, bridge and robotics sectors, has developed twelve 5-minute scientific-story micro-videos: from the low-temperature brittle fracture of the Titanic to the instability of the Falcon 9 rocket’s propellant tank, to the 200,000-cycle fatigue challenge of foldable screens. Each story follows a four-act narrative of “historical conflict-scientific question-mechanical insight-engineering lesson”. For instance, in the late 18th century, French scientist Coulomb established through delicate torsion-balance experiments the linear distribution law that “shear stress on a cross-section is proportional to the distance from the axis”, laying the foundation for the theory of torsion of circular shafts and later guiding Saint-Venant to the exact solution of column torsion. The experimental design and error analysis involved reveal how early scientists approached the truth step by step with rudimentary instruments. Conversely, the collapse of the Wuxi elevated bridge on 10 October 2019 provides a sobering modern footnote to “stability theory”: a truck overloaded by 187 t travelling eccentrically generated a huge eccentric bending moment on the single-column pier, causing the structure to snap from compression instability to overturning failure in an instant. The wreckage and mechanical calculations corroborated each other, lucidly illustrating the conclusion proposed by Musschenbroek in 1729 that “buckling load is inversely proportional to the square of the column length”, a truth that still warns the engineering community today. These two narratives separated by two centuries—one a faint candle in the laboratory, the other a thunderous crash on an urban avenue—point to the simple yet brutal truth of mechanics of materials: once stress exceeds the limit the material can bear, disaster will recur regardless of historical era. These stories guide students, under the national new-engineering development concept, to pursue craftsmanship with excellence, to respect mechanical laws as they respect life, and to understand that any negligence in calculation or any fluke in overloading could be the fuse of catastrophe. Only by anchoring every link of the “external force-internal force-stress-deformation-failure” chain to reverence and precision can knowledge truly serve human safety and progress.

3.3. Seminar-Style Teaching to Transform Passive Learning into Active Learning

To implement seminar-style teaching in Mechanics of Materials, the classroom can be converted into a continuous field of “problem-driven-collaborative inquiry-immediate feedback”. The following measures suffice to shift students from passive reception to active construction. First, a scenario-seminar on “cantilever beam end deflection” is organised: students must intuitively estimate, then derive by energy method, and finally compare results via cloud simulation by scanning a QR code; error discussion naturally

leads to re-examining the stiffness concept. Second, a role-debate around “critical load of slender columns” is staged: one side upholds the universality of Euler’s formula, the other raises defect-sensitivity doubts.[7] On-site consultation of codes and literature prompts students to stitch theory to engineering experience. Third, in the segment on “bending normal stress of composite beams”, real enterprise data are introduced; students, in groups, must rapidly check safety factors from equivalent cross-sections to final values, display results instantly on posters, and refine model assumptions through peer review with only minimal faculty guidance. Fourth, portable three-point-bending mini-experiments juxtapose the “linear stress-strain stage” with the “necking failure” phenomenon; through hands-on loading and real-time curve comparison, students spontaneously question the applicability limits of strength criteria. These measures all take classical knowledge points as carriers but return the initiative of derivation, questioning, verification and reflection to students, turning the classroom into a continuously generated thinking site.

3.4. Integrating Experiments and Practical Teaching to Cultivate Students’ Scientific Research and Practical Ability

In the long chain of Mechanics of Materials teaching, practical instruction can be embedded not only in classroom experiments but also extended along four escalating tiers: “course-project-competition-industry”. Before theoretical lectures, “micro-reconnaissance” can be assigned: students use mobile phones to photograph cracks and deflections of campus bridges or building joints, and then back-calculate possible external and internal force distributions to establish problem awareness before formulas are introduced. At chapter transitions, a “numerical simulation workshop” can be opened to guide students to model the same beam with simple finite-element software using both Euler-Bernoulli and Timoshenko beam theories and compare the differences to deepen understanding of shear deformation effects.[8] Mid-semester, “university–enterprise joint mini-projects” can be launched, bringing real failed parts (broken connecting rods, buckled brackets) provided by companies into the classroom; student teams complete the full workflow from geometric surveying and material testing to failure analysis. After the course, docking with a “structural design challenge” requires students to apply their knowledge to design lightweight beam structures for drone landing gears or robotic arm joints, going through a closed loop of concept-calculation-manufacture-loading-iteration to achieve seamless translation between knowledge and industrial language. In addition, summer research training and university student innovation and entrepreneurship projects can be integrated to encourage students, under instructor guidance, to directly apply energy methods and stability theories from lectures to performance prediction and optimisation of novel structures such as deployable solar panels and folding bridges, extending a one-off experiment into a continuous practice stream throughout the undergraduate stage.

4. Conclusion

Looking back on the trajectory of this teaching reform, we

have used a “knowledge tree” to clarify the system, a “story chain” to arouse emotion, a “seminar arena” to ignite thinking, and a “practice stream” to forge ability, elevating Mechanics of Materials from “formula accumulation” to a “problem-driven, interdisciplinary, innovation-oriented” engineering base. The course is no longer merely the static transmission of stress-strain curves but has become a dynamic cognitive river: students cycle through the logical chain of external force–internal force–stress–deformation–failure, traverse between real engineering wreckage and cloud simulations, and ultimately transform abstract symbols into perceivable, verifiable and optimisable structural language. Looking ahead, we will continue to open the boundaries of the classroom, allowing new materials, new algorithms and new scenarios to flow in in real time, so that every loading event and every cloud image becomes an opportunity for dialogue between students and the industrial frontier; The “tree–chain–layer” framework will continue to sprout new branches with knowledge renewal, and the ecology of “story–seminar–practice” will accompany students from undergraduate studies to graduate school and even their professional careers. Only thus can the ancient yet ever-new discipline of Mechanics of Materials truly become a powerful engine for new-engineering talent and continue to shine with the rational brilliance of force and beauty in the vast sea of future industries such as intelligent manufacturing, commercial aerospace and flexible electronics.

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