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Exploration in Constructing Capstone Courses for Cultivating Mechatronics Talents under the Background of "New Engineering"

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Abstract: The cultivation of applied talents under the "New Engineering" background is a significant issue in current educational reform. This paper explores the teaching objectives and methods of the practical course on generative design and additive manufacturing. The course employs a combination of theory and practice to teach students the structural design process from conceptualization to product prototyping, utilizing relevant professional knowledge, including hand-drawn sketches, CAD, CAE, design optimization, additive manufacturing, and structural testing, to guide students in completing the design and manufacturing of structures. Through the study of the generative design and additive manufacturing practical course, students have acquired some of the core knowledge and skills required for the latest structural design and manufacturing. This has also greatly contributed to the cultivation of students' comprehensive qualities and innovative capabilities.

1. Introduction

Compared to traditional engineering disciplines, "Emerging Engineering Education" not only incorporates the strengths of conventional disciplines but also aligns with the developmental trends driven by new markets, technologies, and requirements [1-3]. It reflects on the new standards for engineering talent in society and the innovative training models in higher education, placing greater emphasis on the cultivation of application-oriented professionals. Surveys indicate that many students are eager to learn advanced design methods and manufacturing techniques. Additive Manufacturing (AM) fabricates structures by layering materials, enabling the free "growth" of highly complex geometries. In recent years, AM has rapidly evolved and been widely adopted across various industries. However, there is a noticeable shortage of corresponding design talent, primarily because the design methods taught in current curricula are mostly tailored to traditional manufacturing processes such as turning, milling, and casting. The manufacturing approach of AM is fundamentally different from these traditional methods, and structures designed based on conventional techniques cannot fully leverage the technological advantages of AM to produce high-performance components. At the same time, students should recognize that every manufacturing method has its limitations. Understanding how to harness the technical advantages of AM while mitigating the drawbacks associated with its processes is also a critical aspect. Generative design, building on traditional design methods, applies computational power and optimization techniques to innovative structural design, with topology optimization being one of its most typical representatives. Combining topology optimization with AM technology can effectively design and manufacture high-performance mechanical structural components. Therefore, it is essential to offer a practical course on generative design and additive manufacturing. On one hand, such a course aims to equip students with the fundamental workflow of structural design and the practical ability to integrate CAD, CAE, and AM technologies. On the other hand, it guides students to adopt scientific thinking methods, enhancing their capacity to analyze and solve problems[4]. Through this course, students will be able to systematically integrate the knowledge they have acquired, achieving a comprehensive understanding, practical application, and targeted learning, thereby fostering their practical skills.

2. Introduction to Generative Design and Additive Manufacturing Course

Guided by the teaching philosophy of cultivating applied talents for the country [5], this course was developed. It guides students through the entire product design, manufacturing, and testing process—from modeling, simulation, and optimized design to additive manufacturing and experimental testing—enabling them to complete the design of a complex mechanical component. Through this course, students experience the full cycle of a mechanical product, from conception and design to optimization, manufacturing, and testing, by comprehensively applying technologies such as computer-aided design, finite element simulation, topological optimization, and additive manufacturing, ultimately completing the design of a product prototype. The innovative aspect of this course lies in its integration of additive manufacturing with structural optimization design theory, demonstrating how human creative thinking and computer-aided engineering interact during the design process to achieve the design and manufacturing of high-performance innovative structures. Additionally, by combining finite element simulation with experimental testing, the course helps students understand the complementary relationship between simulation and experimentation.

Through a combination of theory and practice, primarily in the form of project-based learning, the course enables students to design, simulate, manufacture, and validate mechanical structures. By studying this course, students will be able to integrate their previously acquired knowledge in solid mechanics, engineering materials, computer-aided design (CAD), computer simulation (CAE), and experimental testing. They will also gain a certain understanding of additive manufacturing technology through hands-on manufacturing processes. Furthermore, the course helps students recognize the capabilities and limitations of human thinking, experience, and computational tools in the design and manufacturing processes. It equips them with a preliminary mastery of the main procedures, design approaches, and methodologies of structural design, while fostering their creative thinking.

3. Teaching Objectives and Course Process

The objective of this course is to provide students with an opportunity to utilize the latest design methods and manufacturing technologies to achieve structural design and manufacturing, enabling them to design, manufacture, and validate structures quickly and effectively. Through a phased and progressive innovative teaching methodology, students are encouraged to integrate the knowledge they have acquired, stimulating their interest in active learning and gradually cultivating their ability to comprehensively apply what they have learned in practice and innovation [6–9]. The course is primarily divided into two stages, progressively fostering students' innovation capabilities and engineering practical skills.

The first stage is the experience-based design phase, which relies on the designer's expertise. In this stage, students address design problems through empirical design, create structural sketches, and use computer-aided design (CAD) to transform these sketches into 3D models. The designed structure is then simulated using finite element analysis (CAE), and the empirical design is iteratively refined based on the simulation results until it meets the design requirements. The design model is subsequently manufactured using additive manufacturing technology, and finally, experimental tests are conducted on the manufactured model to validate the effectiveness of the design solution and ensure it meets the design specifications. The outcome of this stage is a finalized design proposal.

The second stage is the computer-based optimization design phase. In this stage, the design problem is abstracted into a mathematical optimization model, and topological optimization techniques are employed to carry out the optimization design, resulting in an optimized design solution. The optimized design is then translated into a 3D model using computer-aided design (CAD). The structure is again simulated using finite element analysis, followed by manufacturing the design model with additive manufacturing technology. Finally, experimental tests are conducted on the manufactured model to validate the design, and the finalized design proposal is delivered.

4. Teaching Objectives and Course Process

4.1 Computer-Aided Design (CAD)

Students establish 3D models of mechanical components by modeling both empirical designs and optimized design results. Through this practical process, they deepen their understanding of CAD and the role it plays in structural design. During the structural improvement design process, students may develop numerous modified structures, enabling them to independently recognize how to use parametric modeling to quickly achieve modeling of different configurations and understand the importance of parametric modeling in CAD design.

4.2 Computer-Aided Engineering (CAE)

The CAD model is imported into finite element analysis software to perform finite element analysis on the structure. Through this practical process, students learn the basic workflow of finite element analysis, including geometry import, meshing, material property assignment, boundary condition setup, finite element solving, and post-processing. They understand how to use simulation methods to obtain the structural response under given loads, such as displacement, stress, and strain. By analyzing the design response, students determine whether the structure meets the design requirements. If it does not, they learn how to effectively improve the structural design.

4.3 Additive Manufacturing (AM)

The CAD model is exported as an STL file and imported into additive manufacturing pre-processing software to create a printable data file. Through hands-on 3D printing practice, students learn how factors such as structural printing orientation and support structures impact the final manufacturing outcome. For example, different printing orientations can enable self-supporting structural printing—particularly important for metal structures, where support structures are relatively difficult to remove. Students explore how to achieve effective printing and manufacturing of structures without compromising or minimizing the impact on structural performance, as illustrated in Figure 1. Additionally, this practical process helps students understand the process constraints of additive manufacturing, such as how to consider these manufacturing limitations during the design phase, design structures rationally, and effectively leverage the advantages of additive manufacturing while mitigating its drawbacks.

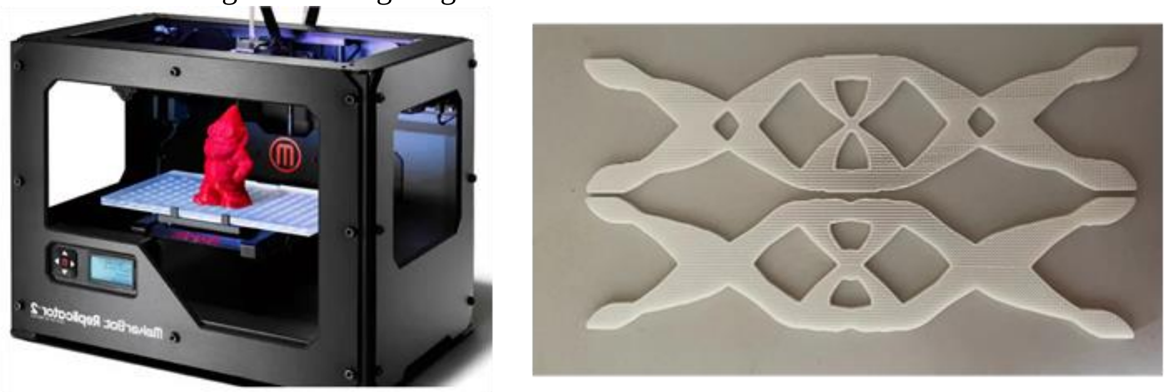

Figure 1 Additive Manufacturing Example

4.4 Experimental Testing

Experimental testing is conducted on 3D printed prototypes, including loading methods and stress-strain measurement techniques, with results compared against simulation data. For most teams, the test results do not align with static finite element simulations. Potential sources of error include boundary conditions, material properties, and the relative compliance between fixtures and test specimens, as illustrated in Figure 2. Students learn how to enhance accuracy in both finite element modeling and experimental testing.

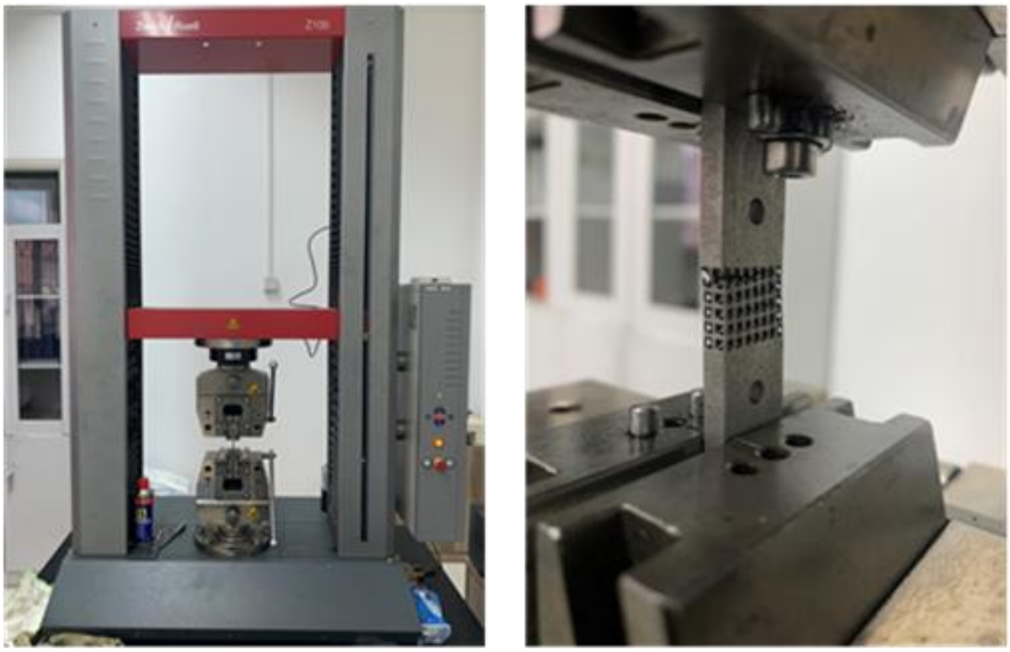

Figure 2 Experimental Testing Process

5. Comprehensive Evaluation System for Learning Quality

With the advancement of educational reforms, the evaluation of teaching quality and students' knowledge acquisition has shown a trend toward refinement and diversification. Establishing a multi-dimensional comprehensive evaluation system serves a dual purpose: it assesses "what students have learned," while also helping teachers identify weaknesses in their teaching methods and gain insights into students' learning progress and outcomes. This, in turn, further enhances teaching quality. By avoiding a single-metric approach, the system enables a holistic evaluation of students' comprehensive abilities.

5.1 Participation in Each Course Segment

In most cases, attendance serves as the most fundamental requirement for assessment. More importantly, it is essential to monitor students' engagement throughout the practical course, such as the autonomy and innovation demonstrated in the structural design process, the accuracy in operating equipment during experimental testing, and the completion of tasks within team divisions. This approach emphasizes both the independence of each student in the practical process and their ability to collaborate effectively within a team.

5.2 Data Processing and Analysis

During the process of structural design and analysis, students are required to correctly process data and utilize software such as data and image processing tools to reprocess the data. This not only evaluates their hands-on operational skills during practical work but also assesses their ability to comprehensively employ computer-based methods for data processing and refinement. Additionally, it helps cultivate their fundamental skills in scientific illustration.

5.3 Flexibility in Analyzing Problems

Students are required to scientifically analyze design outcomes based on their theoretical knowledge framework and present their individual insights. They are encouraged to boldly propose their own ideas, and results do not necessarily have to be unique—as long as they align with the fundamental principles of mechanics, they are acceptable [10]. The focus is on evaluating students' independent thinking skills and innovative mindset. For incorrect or inaccurate conclusions, students are guided to identify the causes and correct their errors.

6. Conclusions

Against the backdrop of the transformation and upgrading of traditional engineering disciplines into "Emerging Engineering Education," course development must also adapt to the evolving times through innovative models. Drawing on practical experience in curriculum development, this paper explores the teaching philosophy of the practical course in Generative Design and Addliaitive Manufacturing. By adopting a project-based teaching approach and a phased, progressive innovation pedagogy guided by projects, the course actively engages students' enthusiasm for learning. It establishes a three-tier practical teaching system focused on cultivating fundamental operational skills, independent design capabilities, and comprehensive innovation abilities. This approach gradually nurtures students to become high-quality talents with a solid foundation, broad knowledge, and innovative capabilities, thereby cultivating applied engineering professionals with strong convictions and robust expertise for the nation.

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