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Incorporating an engineering standard for a team design project in simulation-based design course

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INCORPORATING AN ENGINEERING STANDARD FOR A TEAM DESIGN PROJECT IN SIMULATION-BASED DESIGN COURSE

ABSTRACT

One primary goal of a mechanical engineering program is to train students to be able to conduct mechanical design. Engaging in a mechanical design project offers numerous benefits for mechanical engineering students such as implementation of theoretical knowledge, experience with industry standards, real-world exposure and skills development via life-long learning. Class design projects hosted in technical courses are the most effective approach to gaining skills and improving their abilities to practice mechanical designs. The class design projects in freshman, sophomore, and junior year are typically subject-specific design projects, mainly focused on the subject of the course. A second type of design project is comprehensive design projects, which typically require students to integrate and use skills from several subjects. Students could gain more skills and experience by engaging more comprehensive design projects. Therefore, more comprehensive design projects are needed in junior and senior years for mechanical engineering programs. This paper presents a comprehensive design project, the analysis of the bolted-flange-gasket design project based on API(American Petroleum Institute)-6A standard, which connects a high-pressure tank (5000 psi) to a piping system. In this project, students were required to study and understand the API 6A standard. Then, they were asked to use the API 6A standard to design a bolted-flange-gasket assembly by creating models and selecting materials. Finally, they conducted the FEA simulation to prove that the design would satisfy the design requirement of no oil leakage. This paper will present the implementation of this project, the class survey results and student feedback in the 2023 spring semester.

1. INTRODUCTION

One of the primary objectives of mechanical engineering programs is to ensure that students can conduct mechanical design, as designing products to meet customer and societal needs is a fundamental task for mechanical engineers. ABET (the Accreditation Board for Engineering and Technology) defines Student Outcome 2 as "an ability to apply engineering design to produce solutions that meet specified needs with consideration of public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors"[1]. Consequently, activities related to mechanical design or mechanical design projects are among the core components of a strong mechanical engineering program curriculum[2,3,4].

Conducting design projects is one of the most effective approaches for motivating students to actively engage with course topics, apply their knowledge, and gain hands-on experience with mechanical design projects. Many previous studies have provided examples of design projects incorporated into engineering programs at the freshman, sophomore, junior, and senior levels.

In mechanical engineering programs, freshman-year design projects are typically introduced in courses such as Introduction to Engineering Design or Engineering Graphics[5,6]. In the sophomore year, foundational engineering courses such as Mechanics of Materials and Statics are offered. Design projects are often integrated into these courses to reinforce key concepts[7,8].

As students progress to their junior year, they encounter more advanced engineering courses such as Engineering Dynamics and Design of Machine Elements, which frequently include class design projects[9,10]. In the senior year, application-based technical courses, such as Capstone Design Projects and Finite Element Analysis (FEA) Simulations, are introduced, where design projects are typically essential components of the curriculum[11,12,13,14].

There are different types of design projects in different courses for engineering programs. All of these design projects could be categorized into two types.

The first type of design project is referred to as subject-specific design projects, which primarily focus on a particular subject within a course. Many design projects during the freshman and sophomore years typically fall into this category. For example, some first-year design projects[5] in an introductory engineering design course focused on the engineering design process. The primary goal of these projects was to help students gain a basic understanding of the engineering design process, making them a clear example of subject-specific design projects. In another example, the design projects[6] in engineering graphics course mainly focused on modeling and drawing, with dimensions and material selections provided, instead of being determined in the project itself. This too was a subject-specific design project.

Even in junior or senior years, some design projects may still fit into the first category. For example, in a course on machine element design, projects[10] focused on designing machine components such as gearboxes. These projects included dimension calculations, material selections, and stress/deformation analysis, which were the primary topics of the course, thus classifying it as a subject-specific design project. Similarly, a senior-year project [15] in a mechanical vibration course focused on key topics like natural frequency and damping ratio. The project involved building simple prototypes to demonstrate these vibration properties, but factors like durability, safety, and material selection were not fully considered, so it remained a subject-specific design project. Lastly, in a Finite Element Analysis (FEA) course, design projects[16] centered on applying FEA simulation skills to calculate the stiffness of bolt-joint members. Other aspects of the design were ignored. This, too, is an example of a subject-specific design project.

A second type of design project is the comprehensive design project, which typically encompasses multiple subjects. Capstone design projects [11–14] fall into this category, as they require students to apply all the knowledge they have gained in their education to successfully complete their designs. Other examples of comprehensive design projects include multidisciplinary design projects[17], industry-sponsored design projects[18], and competition-based design projects[19] undertaken during the junior and senior years. These projects demand that students integrate a variety of skills from different engineering courses and subjects. By engaging in comprehensive design projects, students gain valuable hands-on design experience, while integrating everything they have learned in a program into a cohesive design. Therefore, incorporating more comprehensive design projects into mechanical engineering programs would be beneficial.

The mechanical engineering program in our university has a required FEA-simulated related course in senior year. This course typically had two class design projects. The first design project was a subject-specific design project focusing on the FEA simulation tools such as working with the stress concentration factor or the bolt-joint stiffness by FEA simulation[14]. The second design project was a comprehensive design project such as applying FEA simulation analysis on an engine hoist [16], a real device widely used in machine shops.

This paper presents another comprehensive design project centered on the analysis of a bolted flange-gasket joint in accordance with the American Petroleum Institute (API) 6A standard. The project required design teams to interpret and adhere to the API 6A standard, develop the specified bolted flange-gasket joint through modeling and material selection, and perform FEA simulations to confirm that the joint meets design requirements, preventing oil leakage. This paper will outline the project's implementation and discuss the results of a class survey along with student feedback.

2. THE BOLTED-FLANGE-GASKET DESIGN PROJECT

An FEA-related technical course offered in our mechanical engineering program is a required course that utilizes lectures, demonstrations, and case studies to teach students how to use commercial FEA software for stress-strain analysis of components and assemblies. The course includes two lecture hours and four lab hours per week, totaling four credits over a 15-week semester. SolidWorks Simulation is the primary FEA software used in this course.

The course consists of seven units:

- Unit 1: Fundamentals of FEA Theory – Introduces the fundamental concepts of FEA theory, providing students with a basic understanding of how FEA can be used to analyze stress in components with complex geometries and combined loading conditions.
- Unit 2: FEA Simulation on Components – Covers how to use SolidWorks Simulation to perform FEA simulations on individual components.
- Unit 3: FEA Simulation on Assemblies – Explores how to apply SolidWorks Simulation to analyze entire assemblies. Unit 2 and Unit 3 are the core topics of this course, with nine out of the 15 weeks dedicated to these topics.
- Unit 4: FEA Simulation of Natural Frequency – Explains how to determine the natural frequencies of components or assemblies.
- Unit 5: FEA Simulation of Thermal Analysis and Thermal Stress – Demonstrates how to use SolidWorks Simulation to obtain temperature distributions and analyze the resulting thermal stresses.
- Unit 6: FEA Simulation for Fatigue Design – Teaches students how to estimate fatigue damage in components or assemblies using SolidWorks Simulation.
- Unit 7: FEA Simulation for Internal and External Flow – Covers how to simulate velocity and pressure distributions in fluids using SolidWorks Simulation.

This course includes two design projects. After completing Unit 2, students are assigned to the minor design project, which focuses on effectively using SolidWorks Simulation to analyze the stress and deformation of a component. Examples of minor design projects include FEA simulations on stress concentration factors and the stiffness of bolted joints [14].

The second project, known as the major design project, is a comprehensive design project that involves performing an FEA simulation on an assembly. Typically, this project requires students to analyze real products or subassemblies of real products. Since this FEA-related course is offered in the first semester of the senior year—when students have completed most of their technical coursework—we aim to create more complex and realistic comprehensive design projects for this course.

Several years ago, Professor Anthony Duva proposed incorporating engineering standards into one major design project. In collaboration, we developed an analysis of a bolted-flange-gasket joint following the API-6A industrial standard [20].

In the Spring 2023 semester, the bolted-flange-gasket design project was implemented as a comprehensive design project in our section of the course. The following details are based on this implementation.

API flanges are critical components in oil pipelines, used to connect two pipes through a bolted-flange-gasket assembly, as illustrated in Figure 1. For this project, an API flange was used to connect two pipes carrying oil at a pressure of 5000 psi.

Students were required to form teams of two to four members. While students could create their own teams, faculty assisted in assigning teams to those who had not yet formed one. To ensure design variation, each team was assigned a unique innermost flange diameter, as detailed in Table 1. This approach resulted in different part models, loading conditions, and potentially different material selections for each team. The innermost flange diameter was equal to the inner diameter of the oil pipes.

The primary objective of the project was to determine whether the designed flange-gasket assembly would not leak when designed in accordance with the API-6A standard.

Figure 1 The pipeline with API flanges (https://www.mfg-outlook.com/oil-gas-manufacturing)

Table 1 The assigned flange configurations

Design team #	The innermost diameter of the flange	Design team #	The innermost diameter of the flange
Team 1	5-1/8”	Team 4	11”
Team 2	7-1/16”	Team 5	13-5/8”
Team 3	9”	Team 6	16-3/4”

The three objectives of this comprehensive design project were:

(1) Understanding and complying with engineering standards for flange connection design.
For this project, students could download the API-6A standard from the university library. Design teams were required to study this standard and gather relevant information for their assigned flange configurations.

(2) Designing bolted-flange-gasket connections per the API-6A standard.
Students needed to select appropriate materials, determine shapes and dimensions, understand the mechanisms required for proper functionality, and prepare a complete set of engineering documents. These documents included part models, assembly drawings, and detailed technical drawings, ensuring the design could be manufactured.

(3) Conducting FEA simulations to analyze strain, deformation, and stresses.
After completing their mechanical design, students had to verify that their design met the required specifications. This included determining stress, strain, and the factor of safety before manufacturing a prototype for potential physical testing.

This comprehensive design project consisted of four key tasks:

(1) Studying the API Specification 6A – Students reviewed and gained an understanding of the Specification for Wellhead and Tree Equipment, API Specification 6A, which serves as the standard for designing flange connectors.
(2) Applying the standard to design flange connectors – Students used the API-6A standard to design flange connectors based on their assigned configurations.
(3) Conducting an FEA simulation – Students performed FEA simulations to verify that their designs would be leak-free.
(4) Submitting a technical report – Each team compiled and submitted a detailed technical report documenting their design process, analysis, and findings.

To help students to control their pace for this design project, three assignments were created for this project.

The first assignment focused on studying and understanding the API 6A standard, which involved the following tasks:

- Gaining a thorough understanding of the relevant design codes and standards, which is essential before beginning any design work.
- Conducting a comprehensive review of the project requirements and identifying actions such as:
    - Performing a detailed search of applicable API standards for the flange and gasket.

    - Researching relevant websites of industry companies for flange and gasket information.
    - Reviewing bolt standards to assess load capability based on size and grade.
    - Creating a detailed summary of the requirements for the assigned configurations.

The second assignment involved designing the bolted-flange-gasket assembly, with the following tasks:

- Calculate the preload for the bolts of the assigned configuration according to the API 6A standard.
- Create models of the flanges and gasket, including their dimensions and materials.
- Assemble the parts and ensure there are no interferences in the assembly.
- Create detailed part drawings for the flanges and gaskets.
- Develop an assembly drawing for the bolted-flange-gasket assembly.

The third assignment was to conduct an FEA simulation, which included the following tasks:

- Create a partial model to replace the full flange-gasket model for FEA simulations.
- Create bolt connectors to replace the bolt and nut models for FEA simulations.
- Define contacts between the flanges and the gasket.
- Properly define the local and global element sizes for FEA simulation.
- Once the FEA simulation is completed, provide the necessary information for the flanges and gasket.
    - Von Mises stresses plots of each part.
    - Resultant displacement of each part.
    - The contact pressures along one edge of each contact area.

After they completed this comprehensive design project, each team was required to submit a technical report.

3. IMPLEMENTATION

In the 2023 spring semester, the analysis of the bolted-flange-gasket design project was assigned to my section of this FEA-related course.

By the end of week nine, the lectures and discussions on FEA simulation for assembly had concluded. In week ten, the comprehensive design project was assigned, giving students four weeks to complete it. Approximately 30 minutes of each weekly lab session was dedicated to a question-and-answer period, where guidelines were clarified, and students' questions were addressed.

The first assignment, released in week ten, focused on guiding students to study and understand the API 6A standard. Design teams were given two weeks to complete it. The API Specification 6A document was provided, and students were required to review and comprehend the relevant sections related to API flange design.

In the first Q&A session, a schematic of a typical bolted-flange-gasket assembly, as shown in Figure 2, was discussed. Students were guided to understand its structure and working principle. They were also directed to gather three specific pieces of information: (1) a list of materials for the flange, gasket, and bolts, (2) the dimensions of the flange and gasket for their assigned configurations, and (3) the tightening torque or pre-axial load for each bolt.

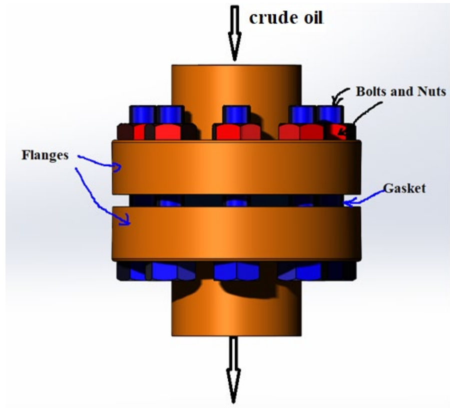

Figure 2 A schematic of a bolted-flange-gasket assembly

Since the API 6A standard is over 400 pages long and had not been covered in previous courses, students were encouraged to seek additional resources. With many companies designing, manufacturing, and supplying API flanges, numerous company websites provide useful information. By exploring these sources, students could quickly find relevant details to support their design project.

The second assignment, released in week twelve, focused on creating models and drawings. Based on the information gathered in the first assignment, design teams had no difficulty determining the dimensions of the flange and gasket and proceeded to create their respective models. Figure 2 illustrates the schematic of the flange-gasket assembly, while Figure 3 provides details on the local contacting area.

According to the API 6A standard, the side surfaces (1 and 2) of the gasket and the oblique surfaces of the flange groove have the same angles. Through the Q&A sessions, students learned two important tips when assembling their models:

- Only one of the gasket's side surfaces could be mated using the "Coincident" constraint with the corresponding oblique surface of the flange.
- Selecting the correct side surface of the gasket for mating was crucial to prevent interference between the gasket and flange.

Ensuring proper mating was essential, as any interference between components would prevent the FEA simulation from running.

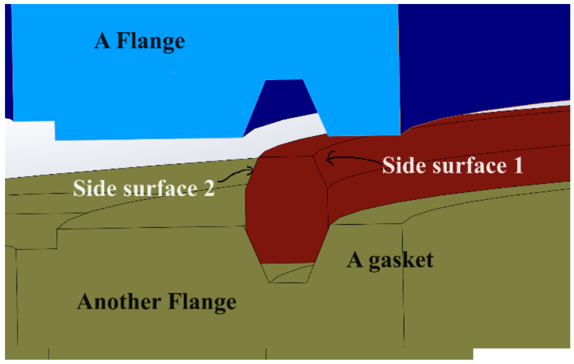

Figure 3 The mates for the bolted-flange-gasket assembly

The third assignment, released in week thirteen, focused on FEA simulation. Design teams had two and a half weeks to complete the simulation and submit a technical report. Several key topics were discussed during the Q&A sessions, including:

- Partial vs. Full Model of Assembly – Since running an FEA simulation on the entire assembly took over hours, a partial model (as shown in Figure 4) was recommended. This model included only one set of bolt and nut, significantly reducing computation time.
- Bolt Connector Approximation – Instead of using detailed bolt and nut models, a bolt connector (a mathematical model) was suggested to simplify the simulation.
- Mesh Controls – Mesh controls were advised for all outer surfaces of the gasket and the surfaces of the flange grooves to improve accuracy.
- Interpreting Contact Stresses – Understanding the contact stresses between the flanges and gasket was a crucial topic. An example graph (Figure 5) showed contact stresses ranging from 120 ksi to 380 ksi—significantly higher than the yield stresses of the flange (66.7 ksi) and gasket (51.0 ksi) materials.

Through discussions, students gained insight into why these high contact stresses occurred and how to determine if leakage would occur for an oil fluid at 5000-psi pressure. They also recognized that, while most engineering designs avoid yielding under normal service loads, yielding at the contact surfaces in this project was both expected and acceptable.

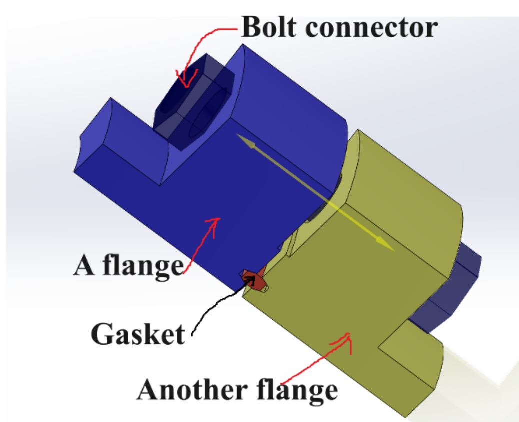

Figure 4 A partial model of the flange-gasket assembly

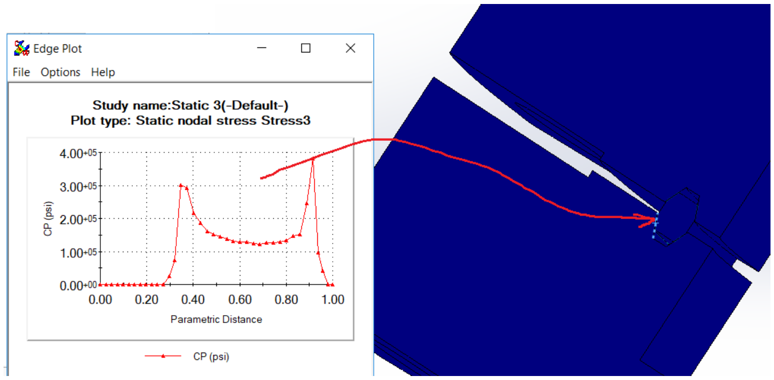

Figure 5 A graph of contacting pressure between the flange and the gasket

Through interactions with students, many expressed that they gained valuable knowledge and accumulated industrial design experience while working on this comprehensive design project. They also noted significant improvements in their FEA simulation skills, including defining local meshing, setting up contact conditions, utilizing partial models to reduce computing time, and properly interpreting simulation results.

4. CLASS SURVEY AND DATA ANALYSIS

To gather more student feedback on the analysis of the bolted-flange-gasket design project, a class survey was conducted through Brightspace at the end of the 2023 spring semester. The survey consisted of three questions and an open comment. The survey questions were:

(1) The major design project helped me to have a better understanding of codes and standards and their implementation in the industry.
☐Strongly Agree ☐Agree ☐No opinion ☐Disagree ☐Strongly Disagree

(2) The major design project significantly facilitated me to implement FEA simulation to solve design project problems.
☐Strongly Agree ☐Agree ☐No opinion ☐Disagree ☐Strongly Disagree

(3) The major design project significantly facilitated me to have a better understanding of FEA simulation skills.
☐Strongly Agree ☐Agree ☐No opinion ☐Disagree ☐Strongly Disagree

(4) Any comments about the major design project

Seventeen out of twenty-two students responded to the survey. The results of the three survey questions are presented in Table 2 and illustrated in Figure 6. Additionally, the percentage of responses categorized as “Agree and above” for each question is summarized in Table 3 and visualized in Figure 7.

According to survey results, 93.33% of students felt that the comprehensive design project improved their understanding of codes, standards, and their application in the industry. Additionally, 86.67% of students agreed that the project greatly helped them apply FEA simulation to solve design problems. Furthermore, 93.33% of students believed the project significantly enhanced their FEA simulation skills.

Table 2 Class survey data

Survey Question #	Strongly agree	Agree	No opinion	Disagree	Strongly Disagree
#1	60.00%	33.33%	6.67%	0%	0%
#2	66.67%	20.00%	6.67%	0%	0%
#3	66.67%	26.67%	0%	6.67%	0%

Table 3 The percentage of "Agree and above" of three survey questions

	Survey Question #1	Survey Question #2	Survey Question #3
Percentage of "Agree and above"	93.33%	86.67%	93.33%

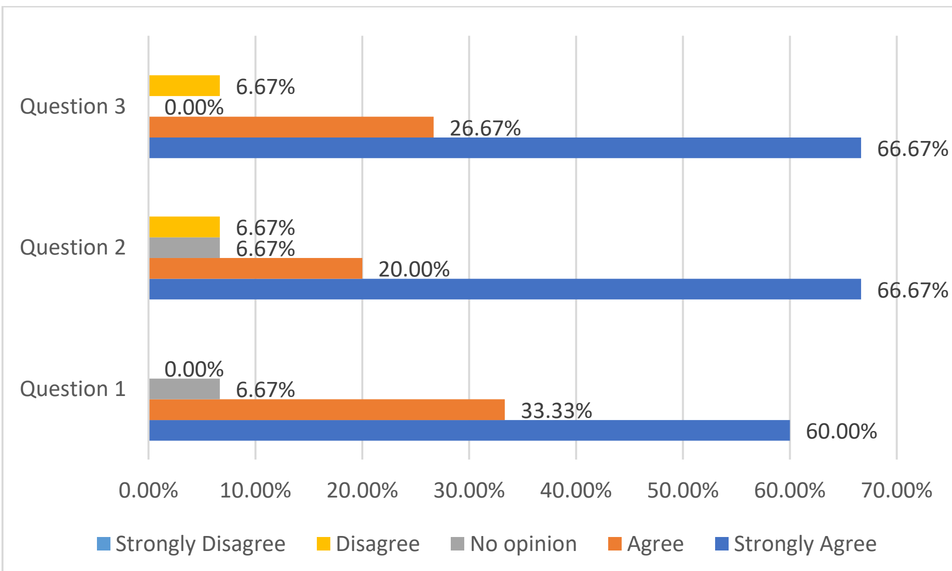

Figure 6 The survey results on three survey questions

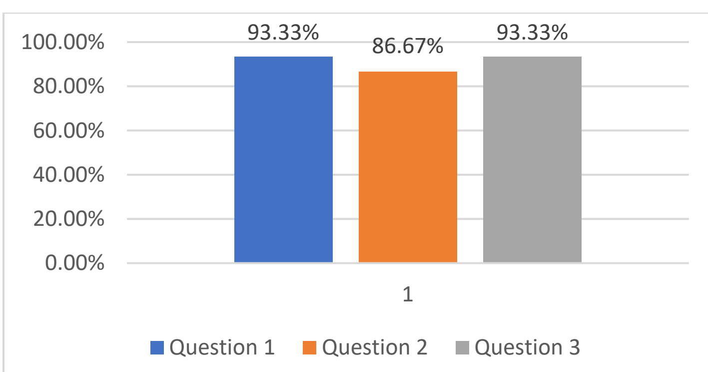

Figure 7 the percentage of "Agree and above" of three survey questions

For the last survey question, some of the comments are listed below.

- "Overall, I believe this was a fairly good design project that encompassed a practical use of SolidWorks simulation. We were able to get a further understanding of API flanges and a more in-depth application of FEA. I also really like the 3 HW assignments related to the project, as they helped keep the team productive, and allowed us to stay on track during the design process."
- "I believe that the major design project was a good way to show students what FEA projects look like in the industry by having us use design guides to help the group design the flange and gasket correctly."
- "The major design project was a good way to learn about industry design standards and FEA by applying it in a real-world scenario through the project. Rather than learning it just through a lecture, it was nice to apply that knowledge to a project that applies in the real world."
- "The major design project helped us collaborate with other students and gain a greater understanding of FEA simulation, applying it to a real situation."
- "I liked how there were three assignments related to the project that helped us do the project in chunks. The three assignments were naturally part of the actual report, so we ended up having a lot of the report already done before we really started."
- "I found it to be an overall interesting project. I learned a bit about codes and standards, as well as how to go about implementing measures from various sources. I will say that the time of the project was rather tough as I also had projects in each of my other classes at the same time, it would definitely have been more enjoyable if done when we did not have much else going on."

5. DISCUSSIONS AND CONCLUSIONS

Class design projects are one of the most effective ways to motivate and help students apply course materials. Most design projects in freshman, sophomore, and junior years focus on specific subjects. However, comprehensive design projects, like senior capstone projects, require students to integrate knowledge and skills from multiple subjects. These projects offer students the opportunity to gain deeper insights and valuable learning experiences. As a result, there is a strong need to include more comprehensive design projects in the junior and senior year technical courses.

The analysis of the bolted-flange-gasket joint according to the API-6A standard was a comprehensive design project. In this project, design teams were required to understand and adhere to the relevant engineering standards while designing the bolted-flange-gasket joint. This involved creating models and assemblies for the parts, selecting appropriate materials, and conducting FEA simulations to verify that the design met the required specifications—specifically ensuring that the joint would not leak oil.

Based on the class survey results, 93.33% of students agreed the design project enhanced their understanding of industry codes and standards; 86.67% found it significantly helpful in applying FEA simulations to design problems; and 93.33% stated it improved their overall FEA simulation skills.

We should aim to introduce more comprehensive projects for junior and senior students, as they provide valuable opportunities for gaining design experience and applying skills and knowledge from multiple subjects. These projects offer significant benefits to students.

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