Incorporating FEA in an Undergraduate Biomechanics Course

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Abstract*—A bioengineering course is offered to senior students in the Mechanical Engineering major as an elective at Penn State Behrend in the first semester of their senior year. On average around 20 students enroll in this project-based course and 72% of their grade depends on three comprehensive group projects, one of which is to design a bone plate for a fractured femur. 6% of the grade comes from an individual application presentation, discussing different circumstances in which the concepts in mechanical engineering can be applied to solve/analyze biomedical problems. Background of physiology is introduced in the class while the majority of applicable engineering knowledge was learned in prerequisite courses, such as statics, dynamics, strength of materials, system dynamics, etc. Finite Element Analysis (FEA), an elective offered in both semesters of senior year, is not a prerequisite for this bioengineering course. Most of students enrolled in our bioengineering course either do not have FEA course or are taking FEA concurrently. Therefore in spite of its popularity in the areas related to biomechanics, thus far FEA has not been incorporated in this bioengineering course. Previously, the fractured femur project utilized the applicable theoretical analyses including those from statics, strength of materials, materials, and machine design. In Fall 2015, the instructor of bioengineering course made an effort to have an FEA study on femur and ensuing presentation be completed by a willing student. This student was taking FEA simultaneously with bioengineering, and was scheduled to present during the last week of semester. The instructor of FEA wrote an introductory manual of FEA procedures to analyze a healthy femur using a CAD model of the femur. Then the student used the manual to initiate the FEA study of the fractured femur. A major challenge to the student was the complicated loading and assembly feature of the bone plus the addition of bone plate. After a several week struggle and independent learning, while guided by the faculty members of bioengineering and FEA, the student was able to accomplish the FEA analysis and presented the results to the class. The discrepancy between FEA results and theoretical analysis was shown to be less than 5% in most results. The presentation also included FEA results for a diverse realistic loading and boundary conditions. Since all students had finished the fractured femur project, they actively participated in a meaningful discussion after the presentation. The completion of this project demonstrated the feasibility and importance of incorporating FEA in our bioengineering course. In addition, the presenting student was able to complete a working manual for the FEA analysis of the fractured femur, which can be passed to the future students of this course. A plan is to include FEA in the project as a bonus activity, and regarding the formation of project teams, the instructor would appoint a member who is enrolled in the FEA course. An assignment or project, based on the present FEA study of the femur, can also be incorporated in the FEA course offered at our campus.

Keywords—Bioengineering, Finite Element Analysis, project-based courses

I. Introduction

Finite element analysis (FEA), because of its versatility in handling realistic models, high solution accuracy, and the benefit of enabling designers/educators to perform 'virtual experiments', is a pivotal course offered in the senior year of many undergraduate mechanical engineering programs. This course can demonstrate diverse engineering concepts especially at an undergraduate level [1]. However, typically FEA application in biomechanics or biomedical engineering is taught in graduate level courses [2]. For undergraduate mechanical engineering students interested in pursuing a career in biomechanics field, a good knowledge of FEA is very beneficial as many significant biophysical and biomechanical studies have utilized FEA models [3-4]. Nevertheless, gaining this knowledge is hard to achieve by the completion of most undergraduate mechanical engineering curriculum. The overall experience of understanding and working with FEA in an undergraduate biomechanics course is limited to a know-how level, not in the problem-solving or practical level [5]. Penn State Erie, the Behrend College offers both FEA and bioengineering courses to senior mechanical engineering students as electives. Many students enrolled in both courses simultaneously, but FEA is not the prerequisite for the bioengineering course. This paper discusses the details of introducing FEA as a practical case study to students, which targets the problem-solving level. We first give the introduction and motivation for this practice, together with the course setup. The design experience in this case study is presented later, followed by the project outcome and discussions.

II. Method

A. Bioengineering course setup

A bioengineering course is offered to senior students majored in the Mechanical Engineering as an elective at Penn State Behrend in the first semester of their senior year. This course is taught in Tuesday and Thursday weekly, with 75 mins each. This course has been offered for the last 10 years, and used to be offered in the spring semester. About five years ago, its offering schedule was switched to fall semester after consultation with previous graduating students. As the only course in bioengineering field, taking it in the fall semester will give students motivation and possibly an opportunity to pursue a job in this field. The prerequisite of this course includes fundamental circuits, fluid mechanics, system dynamics, strength of materials, and intermediate mechanics of materials. Different topics in biomechanics, such as skeletomuscular and motion biomechanics, physiological fluid mechanics, physiological system modeling and control, rehabilitation engineering, etc, are discussed in this course. The focus of the course is the application of engineering knowledge in the context of life science. 75% of skills needed are from previous courses. Background of physiology is introduced in the class, emphasizing the engineering feature of physiological system. For example, circulation system is viewed as one directional pipe flow with the additional effects of adjustable pipe diameter and vessel compliance. The enrollment limit is set to be 24, with between 18 and 24 students enrolled in the last three years. The course is designed to offer both technical depth and breadth to students. 72% of course grade comes from three comprehensive group projects completed by groups of 2 or 3 students. Those projects target technical depths, requiring students to use comprehensive skills in mechanical engineering to solve a problem in biomedical field. 6% of grade comes from an individual's presentation which is presented at the beginning of each 75 mins class from the 3rd week to the last week of the whole semester. The date and topic of presentation is self-selected by students allowing for the requirement that every topic should be unique. Individual presentation targets technical breadth, exposing students to various scenarios of biomedical application. So the focus is experience and awareness. The remaining 22% of course grade comes from homework, online quizzes, seminar attendance and summary, and instructor evaluation.

The first project of three comprehensive projects in bioengineering course is the design of a temporary bone plate for a fractured femur using theoretical analysis (Fig 1). This project is assigned in week 3 and due in week 5. To carry out this project, students need to analyze the loads, stresses, and deflection of femur with or without an inserted metal bone plate using theoretical analysis. It is noted that this project can be accomplished and present a more realistic design using FEA method compared to the solution by classical theory, mainly due to the complex geometry, loadings, and anisotropic properties of femur [3-4].

A few assumptions were made to scale it to an appropriate level for undergraduate students running theoretical analysis: 1) the femur is subject to two vertical force (F_1 and F_2) from the knee joint and hip joint respectively, a combined force/moment from multiple muscles acting at point B, plus a moment from the knee joint; 2) The femur is a hollow pipe with uniform dimension; 3) The femur is isotropic with uniform material properties in all direction; 4) F_2 is applied at greater trochanter instead of femur head as shown in Fig 1. The analysis can be challenging because of, 1) the complex geometry of femur, 2) 3D loads and boundary conditions, 3) composite beam feature of broken femur with plate, and 4) the compromise due to physiological feature of a living broken femur: to help the broken femur recover properly, the designed metal bone plate needs to take over all effective tensile load while maintaining the effective compressive load above a certain level to make sure the remodeled bone will not shrink due to the reduced strain stimulus [6]. Students need to apply the solution skills they learned from statics, strength of material, and intermediate mechanics of materials to complete the project. The average time for each student to finish this project is between 20 to 30 hours, similar to the other two projects.

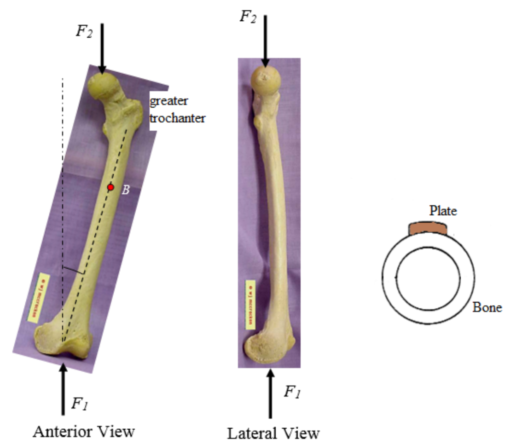

Fig. 1. Loading conditions in femur project

B. FEA course setup

Mechanical engineering students in Penn State Behrend are introduced briefly to FEA in a junior required course, i.e. intermediate mechanics of materials. That course is also one of prerequisites of bioengineering course. In that course, students learned some FEA related skills such as how to create a single 3D CAD model of a simple part, develop finite element mesh, and perform a linear structural FEA on that part. A more in depth understating and applied knowledge of FEA are taught in a dedicated elective course on FEA, offered to our senior students in both fall and spring semesters. In addition to the introductory theory of finite element (FE) formulations, this course covers many application concepts in mechanical engineering such as analyses of structural, thermal, dynamic, modal and harmonic, transient and multistep, and optimization problems using FEA software. Students also are instructed to solve multibody (assembly) models and cases with diverse boundary conditions, both deemed to be essential to complete the femur analysis.

C. Case study of FEA in bioengineering course

Typically more than 50% of students of bioengineering course enroll in FEA course concurrently. A few years ago, the instructor of bioengineering course initiated the effort to incorporate FEA in the bioengineering class at the problem-solving level. The instructor added FEA in the femur project as a 15% bonus and made sure the self-selected student teams had at least one member enrolled in the FEA course. So far, no student groups has accomplish this bonus because: i) most students do not have the proper levels of proficiency in FEA, including students who enrolled in FEA, and ii) the required amount of work for the FEA is too extensive, which is related to the complicate loading of femur coupled with bone plate. In Fall 2015, 23 students enrolled in the bioengineering course. One student, who is taking FEA simultaneously, signed up the last class for the presentation date without a topic. This student agreed willfully to present the FEA results of the femur project at the request of the instructor after week 5. The student is also requested to generate a detail step by step instruction.

At the request of bioengineering instructor, the instructor of FEA wrote a short introductory manual of FEA procedures to analyze a healthy femur using a 3D CAD model of the femur. The 3D CAD model was publically accessible from internet. Then the student used the manual to initiate the FEA study of the fractured femur. After a several week struggle and independent learning, while guided by the faculty members of bioengineering and FEA, the student was able to accomplish the FEA analysis and presented the results to the class, as shown in Fig.2. The discrepancy between FEA and theoretical analysis in one simplified loading scenario was shown to be less than 5% in most results. The presentation also included FEA results for a diverse realistic loading and boundary conditions.

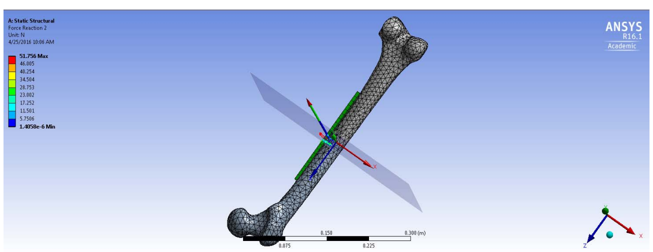

Fig. 2. ANSYS model of the broken femur with plate

III. Results

The outcome of this piloting practice include: 1) a technical presentation which closely tied to one project, and 2) a detail step-by-step instruction for FEA analysis of femur project. Compared to other presentations, this one emphasized the technical analysis and interpretation of results, and was tied directly to problem solving skills. The presenting student spent about 40 hours totally on this assignment, in contrast to the average 5 to 10 hours for other students in the presentation assignment. However, the student described the whole process to be enjoyable. In particular, the student appreciated applying the basic principles of FEA to complex femur project, and be able to visualize the reaction between the bone and plate, which helped to reinforce what the theoretical calculations showed. The students stated: “I found using FEA to model the femur and bone to be very beneficial to my understanding of the course material and also to see how what we learn in school is indeed used in industry. FEA allowed me to view entire section views or bodies experiencing loading at the same time compared to individual points as done with hand calculations. One of the most beneficial parts of using FEA in bioengineering, in my opinion, was the ability to change one value to get a new result without having to recalculate all of the affected equations by hand. An example of this was moving the applied force at the hip from the greater trochanter (the location used in class to simplify the calculations) to the head of the femur, which is the more accurate representation. The process of moving the applied hip force took less than ten clicks of the mouse to obtain results compared to hours of hand calculation.”

The audience of this presentation, other students of this course, also showed great appreciation of FEA in biomechanics research. The agreement between theoretical calculation results and FEA results in one specific loading condition reinforces the students’ fundamental analytical skills in mechanical engineering. They were also impressed with the powerful capability of FEA analyzing various realistic loading conditions.

IV. Discussion

The step by step instruction of FEA analysis of femur project is expected to significantly alleviate the work load for this analysis, especially for students who are minimally exposed to FEA. It is estimated that one student with FEA background can finish the FEA of femur project in less than 3 hours. Its completion is also achievable for students without the FEA background within 8 or less number of hours. Finally we suggest for a future offering of this course to incorporate FEA with a few changes to the course: 1) move the femur project to a later due date to allow students to build up their FEA skills, 2) include at least one student who is enrolled in FEA course in each group, and 3) increase the percentage of this project in the overall course grade to reflect the relatively higher work load of this project compared to the others.

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