ASEE's 123rd Annual • Conference & Exposition • New Orleans, LA • June 26-29, 2016

New Orleans JAZZED about Engineering Education

Paper ID #16238

Using Stress Shielding in Hip Implants as a Case Study to Teach Loading of Composite Beams

Dr. Blake M. Ashby P.E., Grand Valley State University

Blake M. Ashby is an Assistant Professor of Mechanical Engineering in the School of Engineering at Grand Valley State University. His research and teaching interests include the areas of dynamics, kinematics, solid mechanics, movement biomechanics, injury biomechanics, and accident reconstruction. Prior to joining to Grand Valley State, he worked for several years as a consulting engineer with Woolley Engineering Research Corporation and Exponent Failure Analysis Associates. He received a B.S. degree in Mechanical Engineering from Utah State University and M.S. and Ph.D. degrees in Mechanical Engineering from Stanford University. He is a registered Professional Engineer.

Dr. Wendy S. Reffeor, Grand Valley State University

Wendy Reffeor is an Associate Professor of Mechanical Engineering in the Padnos College of Engineering and Computing at Grand Valley State University. She earned her Bachelors from GMI Engineering & Management Institute, Masters from Purdue University and Doctorate from Michigan State University. Her industrial experience includes designing quality systems for Allison Engine Company in Indianapolis. Since joining GVSU, she has focused on introducing design and build projects in traditionally analytical courses in the Engineering Mechanics sequence.

Using Stress Shielding in Hip Implants as a Case Study to Teach Loading of Composite Beams

Abstract

A laboratory activity was developed in which the students modeled and analyzed the femoral portion of an artificial hip replacement as a composite beam. A historical challenge with artificial hip replacements has been that the stiffer artificial femoral component shields the surrounding bone from stresses during physiological activities. This phenomenon, known as "stress shielding," results in bone resorption that can lead to implant failure. In this activity, the students investigated the extent of stress shielding for femoral implants of varying sizes and material properties for different loading conditions. The students discovered that making the femoral component smaller and of more compliant material minimizes the detrimental effects of stress shielding in hip replacements.

The effectiveness of this hip implant activity was studied by comparing it with the traditional laboratory in which the students were tasked with designing a composite beam out of various materials to satisfy rigidity and cost constraints. Students from two laboratory sections completed the traditional composite beams exercise, and students from two laboratory sections completed the hip implant case study. The students from both groups were surveyed before and after the laboratory exercises to determine their confidence in the course material, their interest in the course, and their perception of the real-world relevance of the course.

In the post-exercise survey, students were asked all of the questions from the pre-exercise survey as well as questions to determine the effectiveness of the exercise as a teaching tool and the adequacy of the instruction they received. Students consistently felt the hip implant activity was more effective as a teaching tool for the material and were more interested in biomedical engineering than those completing the traditional exercise. The students who completed the hip implant activity expressed greater confidence in their abilities to interpret the results for bending calculations and to design a machine using bending. Overall, the results of the student perception surveys indicate that the hip replacement activity was a better tool for teaching the composite beam theory and had the added benefit of introducing students to biomedical engineering applications of fundamental mechanics principles.

Introduction

Real-world teaching examples stimulate student learning, increase student engagement, and deepen student understanding of the presented material. Therefore, where real-world examples are readily available, incorporating them into the engineering classroom is considered a best practice. Multiple repositories[1] and best practices resources[2] have recently been added to the available literature (over 6700 papers are found when searching the ASEE conference proceeding search engine for "real world") to encourage incorporation of these examples in individual classrooms. Such examples may be found in many fields and increase the depth of learning for a given principle while exposing the students to different career choices.

Students in many engineering programs, including the one at the authors' institution, are in manufacturing dominated geographical areas. As students studying biomedical engineering are not a large proportion of the population, most students are less likely to have been exposed to biomedical applications of engineering principles than industrial ones. This lack of exposure blinds them to the potential of biomedical engineering as a possible career choice in spite of the fact that this is one of the fastest growing fields of engineering.[3] A study of the femoral stem of a hip implant was presented to students to teach the concept of combined loading of a statically indeterminate member in bending and axial loading and to introduce them to a biomedical engineering application of mechanics principles.

Background

Total hip arthroplasty has been called "one of the most successful orthopaedic interventions of its generation."[4] While attempts at hip replacement date back as far as 1891, the era of modern total hip arthroplasty began in the early 1960's with orthopedic surgeon Sir John Charnley. Most hip prostheses used today are the same in principle to Dr. Charnley's design and consist of three parts: a metal femoral stem, a polyethylene acetabular component, and acrylic bone cement. The first-generation designs which used stainless steel for the femoral stem were very successful, but Charnley reported that 17 cases of fatigue fractures of the femoral component (out of 6500 total implants) had occurred within the first six years of operation.[5]

These fractures led to the introduction of second-generation designs, which made the femoral stems stronger and stiffer to avoid fatigue fracture. The two main strategies to accomplish this were increasing the cross sectional area of the femoral stem and manufacturing them out of a cobalt-chromium alloy, which is stronger, stiffer, and has better fatigue resistance than stainless steel. A follow-up clinical study that compared the first-generation femoral stems to the stiffer stems that followed found that these design changes virtually eliminated fracture of the femoral component.[6]

However, these changes came with an unintended side effect: bone resorption due to stress shielding. The stiffer implants caused less stress to be carried by the surrounding bone tissue, which resulted in bone resorption consistent with Wolff's Law, which states that bone adapts in response to the mechanical loads placed on it.[7] Engh and Bobyn investigated the influence of femoral stem size on bone resorption and reported that stems 13.5 mm in diameter or larger resulted in five times the amount of pronounced bone resorption than stems 12.0 mm in diameter or smaller.[8] Dall, et al. found that the 10-year rate of mechanical failure due to stem loosening was much greater for stiffer second-generation designs (6.7%) than for first-generation implants (1.6%).[6] In response to these design issues, titanium alloys, which have better fatigue properties and much lower stiffness than either stainless steel or cobalt-chromium alloys, have become the material of choice for manufacturing femoral stems.[9] A canine study by Bobyn, et al. found 25% to 35% more bone around the femoral stem for implants made of titanium than for implants made of cobalt-chromium.[10]

Methodology

One group of students (two sections, 30 students) was assigned to complete the hip implant laboratory with one instructor while another group (two sections, 34 students) was assigned to complete the traditional beam bending laboratory with another instructor. All students were enrolled in a sophomore-level mechanics of materials course. Each group was asked to take a survey before being introduced to the assignment and after completing the assigned laboratory. For the hip implant laboratory, 30 students completed the pre-activity survey and 13 students (one of the two sections) completed the post-activity survey. For the traditional laboratory, 34 students completed the pre-activity survey and 31 students completed the post-activity survey.

Traditional Laboratory

In the traditional laboratory, students were introduced to composite beam theory. They were then asked to design a beam to meet specific in-plane and out-of-plane stiffness targets while maintaining minimum cost. They were given a list of materials to be used that included material properties and approximate costs (Table 1). Students were restricted to constructing their beam from five plates. Those plates could be used in any symmetric combination of the materials and sizes given. Examples of possible configurations were also given (Figure 1). Students used a variety of methods to compare the various combinations including analyzing a subset of the possible combinations and choosing one, creating a spreadsheet analyzing all possible combinations, and writing a computer program to analyze all possible combinations.

Table 1 – Composite Beam Layer Options

Material	**Material Dimensions (in)**	**Modulus of Elasticity (psi)**	**Cost per foot ($/ft)**
6061 Aluminum	1/8 × 1	10×10^6	0.72
6061 Aluminum	1/8 × 2	10×10^6	1.21
AISI 1018 Steel	1/8 × 1	29.7×10^6	0.94
AISI 1018 Steel	1/8 × 2	29.7×10^6	1.87
Western Pine Plywood	0.195 × 0.980	11.0×10^3	0.04
Western Pine Plywood	0.195 × 1.965	11.0×10^3	0.08
Particle Board	0.131 × 0.970	3.25×10^3	0.04
Particle Board	0.131 × 1.944	3.25×10^3	0.08
UHMW Plastic	0.137 × 1.036	5.26×10^3	0.09
UHMW Plastic	0.137 × 2.025	5.26×10^3	0.18
UHMW Plastic	0.274 × 1.036	5.26×10^3	0.18
UHMW Plastic	0.274 × 2.025	5.26×10^3	0.36

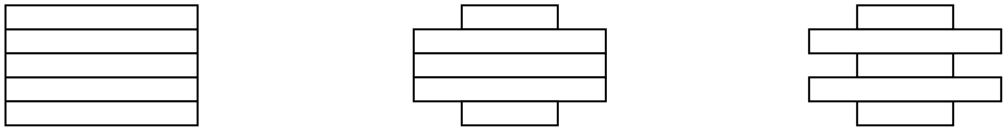

Figure 1 – Some Allowable Composite Cross-section Configurations

Hip Implant Laboratory

In the hip implant laboratory, in addition to introducing composite beam theory, the lecture portion of the lab included a brief description of the anatomy of the implant and description of a model of the femoral stem (Figure 2 and Figure 3). The history of modern hip implants was then explained including early femoral stem fatigue failures, the redesign of the femoral component to make it stronger and stiffer, and the resulting increase in bone absorption due to stress shielding which increased the frequency of implant failures due to loosening. Finally, an analysis of the entire system was summarized to show that making the femoral stem more compliant and more fatigue resistant is the correct engineering decision.

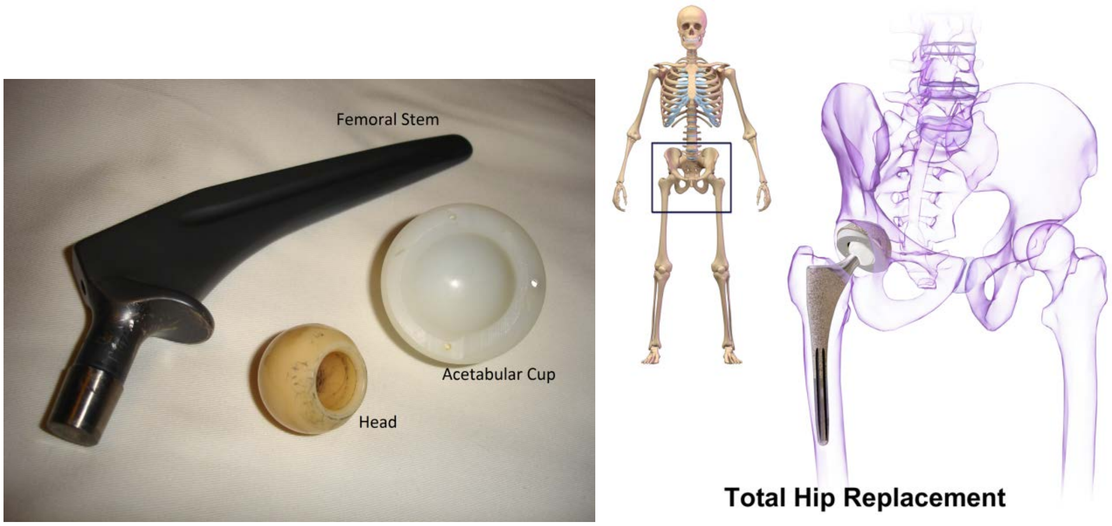

Figure 2 – Hip Implant Anatomy (Nuno Nogueira, 10/14/2006, https://commons.wikimedia.org/wiki/File:Hip_prosthesis.jpg; BruceBlaus, 11/12/2015, https://commons.wikimedia.org/wiki/File:Hip_Replacement.png)

Students were asked to optimize the design of the femoral stem of the hip implant to minimize stress shielding by most closely matching the properties of the femoral stem to those of the bone prior to implant. They were provided the elastic moduli of cortical bone (17 GPa) and of three biocompatible materials: stainless steel (210 GPa), cobalt-chromium alloy (227 GPa), and titanium alloy (110 GPa). The students were also provided with the fatigue strengths of the three implant materials for 10^7 cycles: stainless steel (310 MPa), cobalt-chromium alloy (485 MPa), and titanium alloy (520 MPa).

The original bone was modeled as a hollow tube with outside diameter of 2.5 cm and inside diameter of 1.0 cm. The implant was modeled as a solid cylinder with a diameter ranging from 1.1 to 1.5 cm. A compressive axial load of 3000 N was applied along with a bending moment of 30 N-m. This was to represent the peak hip loading (about 4 body weights applied at about 1 cm from the longitudinal axis of the femur) experienced by an average-sized person walking at 1.5 m/s.[11] When modeling the composite of bone and implant, the internal diameter of the bone was modified to match the diameter of the implant. A depiction of the model used in the analysis is shown in Figure 3.

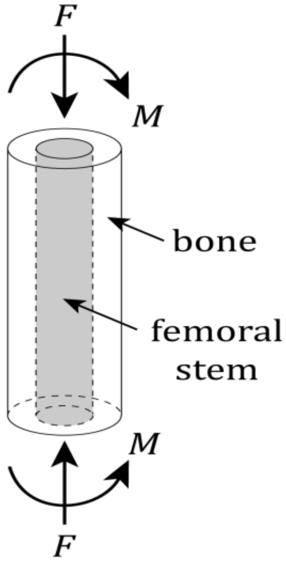

Figure 3 – Model of the Composite Bone/Implant with Loading

Using the principles of combined loading of a statically indeterminate member, the equations for calculating the stress σ in the bone and femoral stem due compressive axial loading F were determined to be:

$$\sigma_{bone} = \frac{E_{bone}F}{E_{bone}A_{bone} + E_{stem}A_{stem}}$$

$$\sigma_{stem} = \frac{E_{stem}F}{E_{bone}A_{bone} + E_{stem}A_{stem}}$$

where the E terms represent the elastic moduli and the A terms represents the cross sectional areas for the bone and femoral stem.

Similarly, the equations for calculating the maximum stress σ in the bone and femoral stem due a bending moment M were determined to be:

$$\sigma_{bone} = \frac{E_{bone}M\left(\frac{d_{bone}}{2}\right)}{E_{bone}I_{bone} + E_{stem}I_{stem}}$$

$$\sigma_{stem} = \frac{E_{stem}M\left(\frac{d_{stem}}{2}\right)}{E_{bone}I_{bone} + E_{stem}I_{stem}}$$

where the d terms represent the outer diameters and the I terms represent the area moments of inertia for the bone and femoral stem.

Using the principle of superposition, the students calculated the maximum stress in the bone and femoral implant due to combined loading of axial compression and bending. They plotted the maximum stress in each material versus diameter of the implant to show the effect of changing material and size of the implant (Figure 4). Additionally, they plotted the effect of each implant on the maximum stress in the bone (Figure 5).

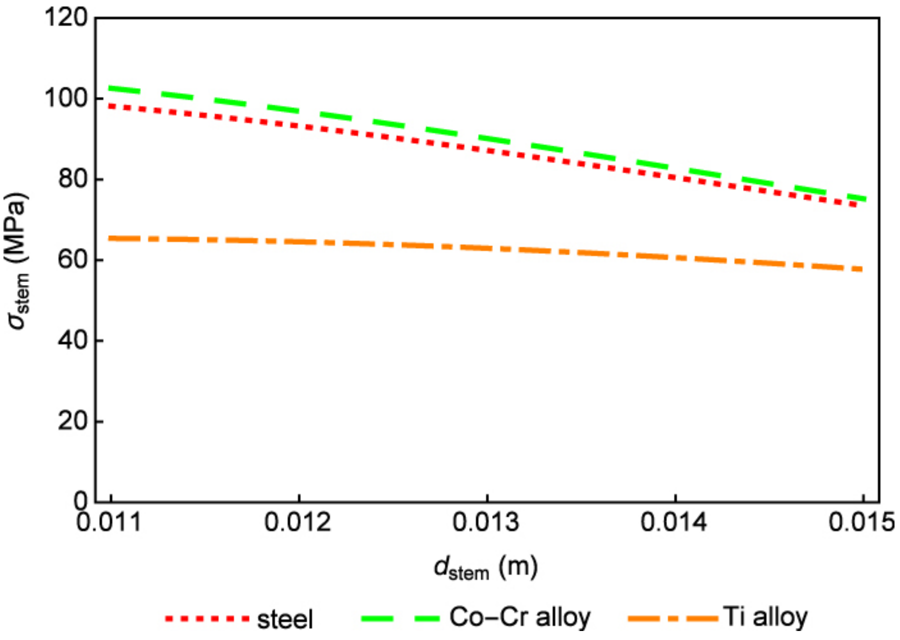

Figure 4 – Maximum Stress in the Femoral Stem for Three Materials

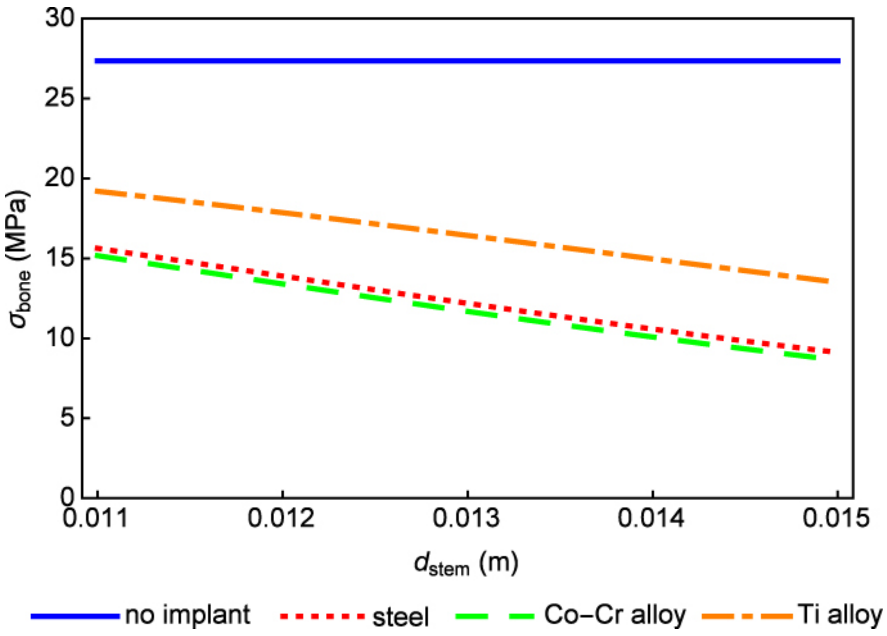

Figure 5 – Maximum Stress in Bone for Three Implant Materials and Unaltered Bone

The students were to analyze these two plots, choose the “best” implant, and comment on how this solution could be improved further. From the results shown in Figure 4, students could quickly see that as the size of the implant is increased, the stress experienced by the implant is decreased for all materials. In addition, the maximum stress in the titanium alloy implant (65.4 MPa) was substantially lower than the stress in the stainless steel (98.2 MPa) and cobalt chromium implants (102.6 MPa). Taking the fatigue strength of the materials into consideration, the students could discover that the maximum stresses in the implants were 12.6% of the fatigue limit for the titanium alloy, 21.2% of the fatigue limit for the cobalt chromium alloy, and 31.7% of the fatigue limit for stainless steel. Thus, while the cobalt chromium alloy was an improvement over stainless steel with respect to resistance to fatigue failure of the implant, the titanium alloy is clearly a better choice.

The stress in the unmodified bone was calculated to be 27.3 MPa. From Figure 5, the students could see that with respect to minimizing stress shielding in the bone, the smallest diameter titanium implant was the best choice. This choice resulted in a stress in the bone of 19.2 MPa, or 70.2% of the original stress in the bone. The largest diameter stem of the cobalt chromium alloy resulted in the most stress shielding with a stress in the bone of 8.6 MPa, or only 31.6% of the original stress in the bone.

Surveys

Students were asked to answer survey questions on a Likert scale (strongly agree, agree, neither agree nor disagree, disagree, strongly disagree). In the pre-laboratory survey, students were asked nine questions about their comprehension of the material, their perception of the usefulness of the material, and their self-efficacy with respect to the material (Table 2). In the post-laboratory survey, these same nine questions were asked in addition to additional questions relating to their interest in biomedical engineering and their feelings about the specific exercise completed (Table 3).

Table 2 – Questions on both Pre- and Post-Laboratory Surveys

Question Number	Question
1	I can calculate, while looking at a sample problem, the bending stress in a beam given the cross-section and loading.
2	I can explain the results of bending stress calculations to another person.
3	I can interpret the results of bending stress calculations and use them determine the adequacy of a part.
4	Given a machine, I can analyze a part and determine if it is strong enough to withstand the loading applied.
5	I can redesign a part to improve its performance in bending.
6	I can design a machine or mechanism to optimize its performance using bending theory.
7	I am interested in the principals being taught in the course.
8	I see the real world relevance of the principals being taught in the course.
9	I am confident in my ability to work on a team to solve complex engineering problems.

Table 3 – Additional Post Laboratory Survey Questions

Question Number	Question
10	I am interested in applying engineering principles to solving biomedical engineering problems.
11	The laboratory on composite beams enhanced my understanding of the principles of bending stress that were taught in this class.
12	The laboratory on composite beams was interesting and worthwhile.
13	Completing this laboratory on composite beams increased my interest in the subject matter presented in the lectures.
14	I am more confident in my ability to analyze deformable body systems as a result of completing this laboratory on composite beams.
15	I have a greater understanding of how the principles taught in the lectures can be applied to real-world engineering problems because of this laboratory on composite beams.

The proportions of students who agreed (i.e., either strongly agreed or agreed) were determined and the 95% Clopper-Pearson confidence intervals for the proportions of students in agreement for each question were calculated. The confidence intervals were compared for each question between hip and traditional exercises and between pre-exercise and post-exercise surveys. Where there was no overlap between two confidence intervals, it was concluded there was sufficient evidence that the proportion in agreement of one was larger than the other. If there was overlap, there was not sufficient evidence that there was a difference in proportions.

Survey Results

The proportions of students who agreed (i.e., agreed or strongly agreed) to the pre- and post-exercise survey questions for the hip replacement and traditional composite beam laboratories are shown in Table 4 and Table 5.

Comparing the pre-exercise surveys for the hip replacement and traditional laboratories, there were three questions for which the confidence intervals did not overlap:

- 100% (88.4% to 100%) of the hip replacement exercise students and 73.5% (55.6% to 87.1%) of the traditional exercise students agreed that they could calculate, while looking at a sample problem, the bending stress in a beam given the cross-section and loading.
- 93.3% (77.9% to 99.2%) of the hip replacement exercise students and 61.8% (43.6% to 77.8%) of the traditional exercise students agreed that they could explain the results of bending stress calculations to another person.
- 100% (88.4% to 100%) of the hip replacement exercise students and 67.7% (49.5% to 82.6%) of the traditional exercise students agreed that they could see the real world relevance of the principals being taught in the course.

Table 4 – Pre-Exercise Survey Results (Percent Agreeing with 95% Confidence Intervals)

Question Number	Hip Replacement Laboratory	Traditional Laboratory
1	100.0 (88.4 – 100.0)	73.5 (55.6 – 87.1)
2	93.3 (77.9 – 99.2)	61.8 (43.6 – 77.8)
3	73.3 (54.1 – 87.8)	70.6 (52.5 – 84.9)
4	73.3 (54.1 – 87.8)	50.0 (32.4 – 67.6)
5	60.0 (40.6 – 77.3)	44.1 (27.2 – 62.1)
6	33.3 (17.3 – 52.8)	29.4 (15.1 – 47.5)
7	90.0 (73.5 – 97.9)	61.8 (43.6 – 77.8)
8	100.0 (88.4 – 100.0)	67.7 (49.5 – 82.6)
9	93.3 (77.9 – 99.2)	82.4 (65.6 – 93.2)

Table 5 – Post-Exercise Survey Results (Percent Agreeing with 95% Confidence Intervals)

Question Number	Hip Replacement Laboratory	Traditional Laboratory
1	92.3 (63.4 – 99.8)	83.9 (66.3 – 94.6)
2	84.6 (54.6 – 98.1)	64.5 (45.4 – 80.8)
3	92.3 (63.4 – 99.8)	74.2 (55.4 – 88.1)
4	76.9 (46.2 – 95.0)	80.6 (62.5 – 92.6)
5	91.7 (61.5 – 99.8)	71.0 (52.0 – 85.8)
6	91.7 (61.5 – 99.8)	53.3 (34.3 – 71.7)
7	69.2 (38.6 – 90.9)	71.0 (52.0 – 85.8)
8	84.6 (54.6 – 98.1)	71.0 (52.0 – 85.8)
9	84.6 (54.6 – 98.1)	41.9 (24.6 – 60.9)
10	76.9 (46.2 – 95.0)	35.5 (19.2 – 54.6)
11	69.2 (38.6 – 90.9)	25.8 (11.9 – 44.6)
12	76.9 (46.2 – 95.0)	63.3 (43.9 – 80.1)
13	76.9 (46.2 – 95.0)	58.1 (39.1 – 75.5)
14	92.3 (63.4 – 99.8)	41.9 (24.6 – 60.9)
15	100.0 (75.3 – 100.0)	83.9 (66.3 – 94.6)

Comparing the pre-exercise and post-exercise surveys for the hip replacement laboratory, there was one question for which the confidence intervals did not overlap:

- The proportion of the students who agreed that they could design a machine or mechanism to optimize its performance using bending theory was 33.3% (17.3% – 52.8%) before the lab 91.7% (61.5% – 99.8%) after the lab.

Comparing the pre-exercise and post-exercise surveys for the traditional laboratory, there was one question for which the confidence intervals did not overlap:

- The proportion of the students who agreed that they were confident in their ability to work on a team to solve complex engineering problems was 82.4% (65.6% – 93.2%) before the lab 41.9% (24.6% – 60.9%) after the lab.

Comparing the post-exercise surveys for the hip replacement and traditional laboratories, there was one question for which the confidence intervals did not overlap:

- 92.3% (63.4% – 99.8%) of the hip replacement exercise students and 41.9% (24.6% – 60.9%) of the traditional exercise students agreed that they were more confident in their ability to analyze deformable body systems as a result of completing this laboratory on composite beams

The small number of students who completed the post-exercise survey for the hip replacement laboratory resulted in large confidence intervals. Therefore, there were some other questions that had overlapping confidence intervals even though there were large differences in the proportions of students agreeing. Comparing the post-exercise surveys for the hip replacement and traditional laboratories, there were four additional questions for the confidence intervals had minimal overlap:

- 91.7% (61.5% – 99.8%) of the hip replacement exercise students and 53.3% (34.3% – 71.7%) of the traditional exercise students agreed that they could design a machine or mechanism to optimize its performance using bending theory.
- 84.7% (54.6% – 98.1%) of the hip replacement exercise students and 41.9% (24.6% – 60.9%) of the traditional exercise students agreed that they were confident in their ability to work on a team to solve complex engineering problems.
- 76.8% (46.2% – 95.0%) of the hip replacement exercise students and 35.5% (19.2% – 54.6%) of the traditional exercise students agreed that they were interested in applying engineering principles to solving biomedical engineering problems.
- 69.2% (38.6% – 90.9%) of the hip replacement exercise students and 25.8% (11.9% – 44.6%) of the traditional exercise students agreed that the laboratory enhanced their understanding of the principles of bending stress that were taught in this class.

Discussion

Despite the remarkable success of modern total hip arthroplasty over the past several decades, some unfortunate design decisions were made on second-generation implants to reduce fatigue failures of the femoral stem. These decisions were to strengthen the implant by increasing its size and using a stronger (and stiffer) material (e.g., cobalt-chromium alloy). While these choices did almost eliminate fatigue failures of the femoral component, the rate of total mechanical failures increased due to the adverse side effect of stress shielding leading to bone absorption and loosening of the implant.[6]

A laboratory activity was developed to give students the opportunity to apply the fundamental theoretical principles learned in an undergraduate mechanics of materials course to investigating the design of the femoral component of a total hip replacement. Using a simple composite beam model with a cylindrical femoral stem component inserted into a hollow cylindrical bone, the students were able to study the effects of changing the materials used in the femoral component and varying the diameter of the stem implant on resistance to fatigue failure of the implant and on stress shielding in the proximal femur.

Using the relatively simple equations derived for this activity, the students clearly demonstrated that increasing the stem diameter would have negative effect on the extent of stress shielding in the surrounding bone. The results from this laboratory activity directly support the findings of a study by Bobyn and Engh, which examined 411 cases of hip replacements and categorized the extent of bone resorption for each case as none, 1st degree, 2nd degree, or 3rd degree.[8] They discovered that for the cases with stem diameters greater than 1.3 cm, 28% had 2nd or 3rd degree bone resorption and for the cases with stem diameters smaller than 1.3 cm, only 6% had 2nd or 3rd degree bone resorption.

The students also discovered that material stiffness has a dramatic effect on the extent of stress shielding. For the loading condition of this exercise, the smallest stem made of the more compliant titanium alloy was able to preserve 70% of the original stress in the bone, while the cobalt-chromium alloy stem of the same size was only able to preserve 55% of the original bone stress. These findings directly support the canine study by Bobyn, et al. that found substantially more bone around the femoral stem with implants made of titanium than with implants made of cobalt-chromium.[10]

Through completing this laboratory exercise, the students learned that by applying fundamental principles learned in a sophomore-level engineering class to the design of the total hip replacement, they could have reached the same conclusions that took many years (even decades) for the actual designers to reach by trial and error. Numerous sophisticated computational models of the total hip replacement and large-scale evaluations of clinical results have been completed to confirm what the students in these laboratory sections demonstrated in a few hours. Certainly, to properly design the components of a total hip replacement, more is required than simply completing this laboratory exercise. However, the power of this laboratory activity was to illustrate to students that sometimes a very simple model can reveal profound and significant principles that can guide future development.

Reviewing the student responses to the pre- and post-laboratory surveys reveal a number of favorable points for the hip replacement laboratory. Completing this exercise increased the students' confidence in using bending theory to design a mechanism to optimize its performance as the students who agreed they could do this increased from 33.3% before the lab to 91.7% after. Also, the student responses demonstrated the feeling that the hip implant activity was more effective in teaching the material than the traditional composite beam laboratory. For example, the proportion of students who expressed increased confidence in their ability to analyze deformable body systems as a result of the laboratory activity they completed was significantly greater for the hip replacement exercise students (92.3%) than for the traditional exercise students (41.9%). Also, a greater proportion of students who did the hip replacement activity

(69.2%) expressed that their understanding of the principles of bending stress taught in the course was enhanced due to the lab than did students who participated in the traditional laboratory (25.8%).

Another stated purpose of the hip replacement laboratory was to introduce students to a biomedical engineering application, which they may not have exposure to otherwise. The students in the hip replacement sections responded favorably to this exposure. After completing the laboratory, 76.8% of these students expressed that they were interested in applying engineering principles to solving biomedical engineering problems, whereas only 35.5% of the students who completed the traditional composite beam laboratory expressed the same interest.

Conclusions

The hip implant laboratory has been successfully implemented in an undergraduate mechanics of materials course. Students were able to use fundamental engineering principles to justify key design concepts guiding the development of the total hip replacement. Students completing this laboratory were more confident in their ability to apply composite beam theory and more interested in applying biomedical engineering principles than their classmates who completed the traditional laboratory exercise.

Acknowledgments

The Statistical Consulting Center at Grand Valley State University is acknowledged for providing their expertise on statistical analysis of the survey results.

References

1. IEEE Real World Engineering Projects. (n.d.). Retrieved January 24, 2016, from http://www.realworldengineering.org/
2. National Academy of Engineering of the Academies. (2012). *Infusing Real World Experiences into Engineering Education*. Washington, DC: The National Academies Press.
3. Bureau of Labor Statistics, U.S. Department of Labor, *Occupational Outlook Handbook, 2016-17 Edition*, Biomedical Engineers, on the Internet at http://www.bls.gov/ooh/architecture-and-engineering/biomedical-engineers.htm (visited January 23, 2016).
4. Knight, S.R., Aujla, R., and Biswas, S.P. (2011) Total Hip Arthroplasty – over 100 years of operative history, *Orthopedic Reviews*, 3, 72–74.
5. Charnley, J. (1975) Fracture of femoral prostheses in total hip replacement: a clinical study, *Clinical Orthopaedics & Related Research*, 111, 105–120.
6. Dall, D.M., Learmonth, I.D., Solomon, M.I., Miles, A.W., and Daveport, J.M. (1993) Fracture and loosening of Charnley femoral stems, *Journal of Bone and Joint Surgery*, 75B, 259–265.
7. Wolff, J. (1869) Über die Bedeutung der Architektur der spongiösen Substanz. *Centralbl. fd med. Wiss*, 54.
8. Engh, C.A. and Bobyn, J.D. (1988) The influence of stem size and extent of porous couting on femoral bone resorption after primary cementless hip arthroplasty, *Clinical Orthopaedics & Related Research*, 231, 7–28.
9. Head, W.C., Bauk, D.J., and Emerson, R.H. (1995) Titanium as the material of choice for cementless femoral components in Total Hip Arthroplasty, *Clinical Orthopaedics & Related Research*, 311, 85–90.

10. Bobyn, J.D., Glassman, A.H., Goto, H., Krygier, J.J., Miller, J.E., and Brooks, C.E. (1990) The effect of stem stiffness on femoral bone resorption after canine porous-couted total hip arthroplasty, *Clinical Orthopaedics & Related Research*, 261, 196–213.
11. Andriacchi, T.P. and Hurwitz, D.E. (1997) Gait biomechanics and the evolution of total joint replacement, *Gait and Posture***,** 5, 256–264.