An Integrated Active Learning Approach for Understanding Fatigue Theory

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Abstract

It is well known that more than 90% of metal components in mechanical systems fails due to fatigue. With this in mind, a basic working understanding of fatigue theory is very important to mechanical engineering students. Fatigue theory, however, is only covered with a few lectures in a typical undergraduate mechanical engineering program's curriculum. Typical treatment could be as few as four lectures during two weeks in our mechanical program at Wentworth Institute of Technology. Because of this, some students were typically confused about fatigue theory and might not have a basic working understanding of fatigue theory. Students will typically develop a better understanding of a topic if the same topic is presented to students in different ways. To facilitate the development of a basic working understanding of fatigue theory, we proposed an integrated active learning approach for teaching fatigue theory. This included four different exposures to discuss and explore fatigue theory. These four different approaches were lecturing & homework assignments, physical fatigue testing, FEA simulation of fatigue life of fatigue specimens, and the theoretical calculation of fatigue life of fatigue specimens. After the proposed approach was successfully implemented in the spring semester of 2017, we interviewed some students and conducted a class survey to obtain feedback regarding the approach presented in this paper. Student feedback indicated that students benefited from this integrated active learning approach for teaching fatigue theory. 100 percent of students agreed that they had a much better basic understanding of fatigue theory through this multi-faceted approach. This paper will present and explain in detail the integrated active learning approach for teaching fatigue theory. The class survey data analysis is also presented and analyzed.

1. Introduction

Fatigue is defined as failure under a repeated or varying load. This load never reaches a level sufficient to cause failure in a single load application. Fatigue damage or failure is initiated and induced through some defects on the surfaces and/or inside components. The defects could be manufacturing process induced scratches on the surfaces or dislocations, impurities, micro-cracks or micro-cavities inside components. These defects are randomly scattered in components, and some of these defects could be activated due to the cyclic loading of fatigue and become initial cracks which cause final fatigue failure [1,2,3]. Students must understand there is always some sort of defects in metal components in a mechanical system. Loading for any mechanical system is almost always cyclic loading. Given the cyclic nature of most mechanical systems, the main failure mode for metal mechanical components is fatigue related. It is well known that more than 90% of the metal components in the mechanical system fails due to fatigue. Given the primary failures encountered in mechanical design, a good basic working understanding of fatigue theory is very important to be developed in mechanical engineering students.

The fatigue strength or test data should be described by the random variables, that is, statistical approach. However, for undergraduate program, fatigue test data are typically described by developing Stress (S) vs. average Cycles (N) to failure (S-N) curves. These curves are the functions of stress amplitude, mean stress and the average number of cycles at failure. The fatigue strength of a component is significantly affected by inherent component defects and loading conditions. As such, the material strength design limit is reduced thru the application of modification factors, often linked with component stresses thru a variety of fatigue failure theories [1,2,3]. Fatigue theory is typically perceived as very complicated to our students and theories are viewed as still developing.

In a typical mechanical undergraduate program curriculum, fatigue theory is usually addressed in one chapter of the text and covered in two weeks of lectures in courses such as Advanced Mechanics of Materials or Design of Machine Elements. In this traditional approach, we simply covered fatigue theory in lectures and assigned homework hoping for students to implement what they had learned. With only a few lectures covering fatigue theory, students were typically confused about fatigue theory and were not developing a basic working understanding of fatigue theory implementation in design. We quite often found that some students were not able to conduct simple fatigue design analysis and/or avoided fatigue-related design calculations in their senior design projects.

Various publications address the fact that students will have a much better understanding of a topic if the same topic was presented to students in different ways [4,5,6]. Conducting physical fatigue testing demonstrates to students that specimens will not fail in the first loading application but will fail after a number of repeated cycles. The addition of physical test demonstrations significantly improved students' understanding of fatigue theory [7, 8, 9]. Numerical simulation tools such as FEA (Finite Element Analysis) programs have become a wonderful and necessary tool for mechanical engineers and students [4, 10, 11, 12]. FEA software was also frequently implemented in classrooms to conduct fatigue analysis [12~15] to help students visualizing fatigue analysis.

To facilitate students developing a basic working understanding of fatigue theory, we developed an integrated active learning approach for teaching fatigue theory. This approach was successfully implemented into the curriculum for "Advanced Mechanics of Materials" in the 2017 spring semester. The approach included four different exposures to discuss and to explore fatigue theory: lecturing with associated homework assignments: physical fatigue tests in the laboratory; theoretical calculations of fatigue life for fatigue specimens; and FEA simulation of fatigue life for fatigue specimens. After the proposed approach was successfully implemented, we interviewed several students and conducted a class survey to obtain feedback regarding the new approach. Feedback indicated that students benefited from this integrated active learning approach for teaching fatigue theory. The 100 percent of students agreed they developed a much better working understanding of fatigue theory through this approach. This paper will present and explain in detail the integrated active learning approach for teaching fatigue theory along with the survey results.

2. The integrated active learning approach for teaching fatigue theory

MECH4225-Advanced Mechanics of Materials was a 3-2-4 (3 lecture hours-2 lab hour-4 credits) credits course which had 2 one-and-half-hour lectures and one two-hour laboratory per week. Main topics of the course were stress and strain calculations, failure theories resulting from static loading, fatigue failure resulting from cyclic loading, and design of typical mechanical components. The textbook used for this course was Shrigley's Engineering Design [1]. According to the syllabus of this course, fatigue theory was covered in two-weeks out of the total 14-week-semester. For this course, we had both lecture and laboratory, so we developed and implemented an integrated active learning approach for teaching fatigue theory which included four different exposures to discuss and to explore fatigue theory. The four aspects of the proposed integrated active learning approach will be described and presented in detail.

A: Exposure one: lecturing and homework assignment

Lecturing is still and will always be one of the main approaches for teaching and delivering knowledge to students. Four lectures in two weeks, based on chapter 6- "Fatigue Failure Resulting from Variable Loading" in Shrigley's "Mechanical Engineering Design" [1], explained, discussed and demonstrated the fundamentals of fatigue theory. Three homework problems were assigned in which students were asked to practice and to implement what they learned thru the lecturing and studying. Because of a short period of time allotted for teaching fatigue theory, the modified Goodman approach and the component under a constant cyclic load were the focus of this first exposure. The main objective of this first exposure was to provide students with basic tools necessary to conduct a fatigue analysis for a component under a constant cyclic load. The main topics of the four lectures and three homework assignments are as follows.

- **Lecture 1-Introduction and the S-N curves of fatigue specimen.**

  The main topics of the lecture 1 included: (1) the definition of fatigue failure, (2) examples of fatigue failures, (3) details of the fatigue damage mechanism, (4) laboratory fatigue test conditions, (5) S-N curves for fatigue specimens, (6) the simplified S-N curves based on ultimate strength, (7) determination of fatigue strength at a given number of cycles to failure, and/or to estimate the fatigue life (the number of cycles to failure) at a given cyclic loading utilizing the simplified S-N curves, and (8) demonstration examples.

  The desired learning outcomes of the lecture 1 were: (1) to understand the definition of the fatigue failure and the fatigue damage mechanism, (2) to interpret S-N curves, (3) to build the simplified S-N curve and to use it to determine fatigue strength or to estimate the fatigue life of fatigue test specimen.

- **Homework assignment #1**

  Homework assignment #1 was assigned for the lecture 1, which contained problems: (1) interpret S-N curves, (2) build a simplified S-N curve of a fatigue specimen and use it to determine fatigue strength at a given number of cyclic stress cycles and to estimate the fatigue life at a given cyclic stress level. The objectives of this homework assignment were (1) to be able to build a simplified S-N curve of a material when the actual fatigue test S-N

curves were not available (this is typical case in reality) and (2) use the simplified S-N curve to obtain approximate fatigue strength or the fatigue life of the material.

- **Lecture 2-Fatigue strength of components**

The main topics of lecture 2 included: (1) the differences between a standard fatigue test specimen and actual components, (2) fatigue strength of materials and Marin modification factors, (3) the simplified S-N curves of materials which includes the Marin modification factors, (4) use the simplified S-N curves of the component to determine the fatigue strength at a given number of cycles and the fatigue life at a given cyclic stress, and (5) demonstration examples.

The desired learning outcomes of the lecture 2 were: (1) to obtain fatigue strength of a component or build the simplified S-N curves of a component, (2) use the simplified S-N curves of the component to obtain fatigue strength at a given number of cycles and to estimate the fatigue life of a component at a given cyclic stress.

- **Homework assignment #2:**

Homework assignment #2 was assigned for the lecture 2, which contained problems: (1) build the simplified S-N curves of a given material, (2) use it to determine component fatigue strength at a given number of cyclic stress cycles to estimate a component fatigue life at a given cyclic stress level. The objectives of this homework assignment were: (1) be able to build a simplified S-N curve of a component and (2) use the simplified S-N curves of a component to obtain approximate fatigue strength or the fatigue life of a component.

- **Lecture 3: fatigue stress concentration factor and fatigue theory**

The topics of the lecture 3 included: (1) the fatigue stress concentration factor, (2) characterizing fluctuating stresses, (3) use of the endurance limit to design a component under fatigue loading, (4) fatigue analysis failure criteria for fluctuating stress using the modified Goodman approach. The focus of this lecture was only constant cyclic stress and the modified Goodman approach.

The desired learning outcomes of this lecture were: (1) be able to determine the fatigue stress concentration factor, (2) be able to use the endurance limit to design a component which has an infinite life, and (3) be able to use the Modified Goodman approach to design and analyze a component under a constant cyclic stress.

- **Lecture 4: Implementation of fatigue theory for component design under constant cyclic stress**

The topics of the lecture 4 included (1) use the modified Goodman approach to run one demonstration of fatigue design with an infinite life, (2) use the modified Goodman approach and the simplified component S-N curves to estimate the fatigue life of a component when the component doesn't have an infinite fatigue life.

The desired learning outcome of this lecture was that students were able to run the fatigue design or estimate fatigue life by using the modified Goodman approach when the component was subjected to a constant cyclic stress.

- **Homework assignment #3**

Homework assignment #3 was assigned for the lectures 3 and 4. It included the following problems: (1) design of a simple component under a constant cyclic stress with infinite fatigue life, and (2) calculate the fatigue factor of safety of a component with a given constant cyclic loading and (3) estimate the fatigue life of the component when the infinite life fatigue factor of safety was less than 1. The objective of this homework was to help students develop their working knowledge in the application of fatigue theory to run simple fatigue design analysis on a component with a constant cyclic loading.

B: Exposure two: Physical fatigue testing

The laboratory utilizes an Instron 8801 fatigue test machine as shown in Figure 1 to conduct fatigue testing of a specimen with cyclic axial loading. The fatigue specimen was a steel rectangular sheet-type flat fatigue test specimen, shown in Figure 2, designed according to ASTM STM E466 – 15, Standard Practice for Conducting Force Controlled Constant Amplitude Axial Fatigue Tests of Metallic Materials[16]. Since the specimen was based on 12 Gage steel with a thickness of 0.105", the specimen was easily buckled during fully reversed loading fatigue tests. To avoid possible buckling of the fatigue test specimen, the loading cycle applied a tension and released loading back to zero which produced an axial fluctuating stress as shown in Figure 3 for testing.
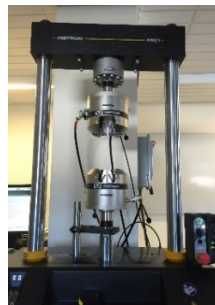

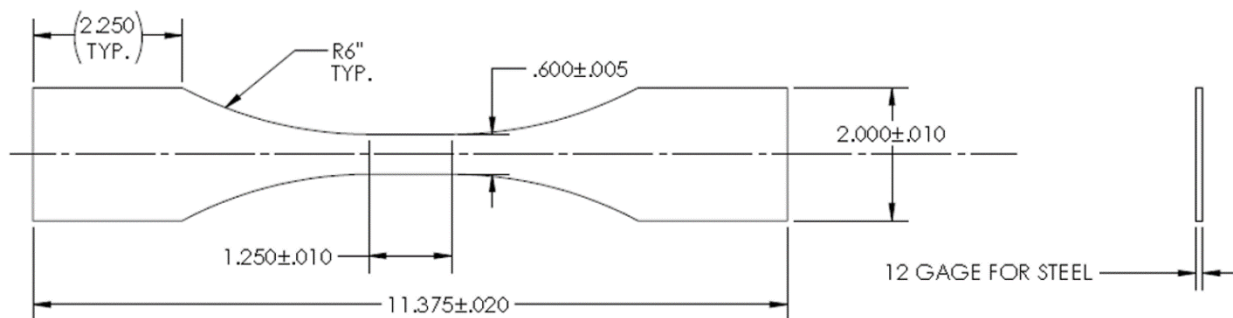Figure 1: Photo of Instron 8801 fatigue test machine

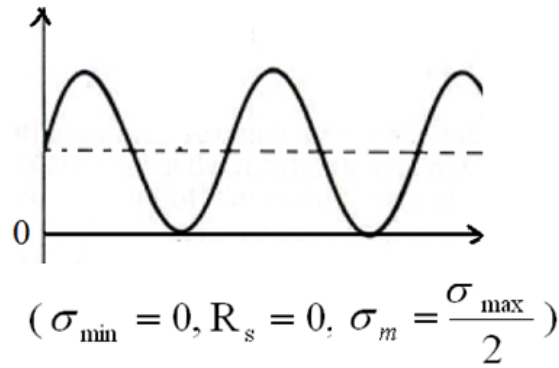Figure 2: Rectangular sheet-type flat fatigue test specimen

$$(\sigma_{min} = 0, R_s = 0, \sigma_m = \frac{\sigma_{max}}{2})$$

Figure 3: Loading induced cyclic stress plot

The base material for the test specimen was 12 gauge thickness A1008 steel sheet The mechanical properties of this steel sheet was obtained by tensile tests [17] conducted in a previous laboratory and listed in Table 1 along with the fatigue loading conditions.

Table 1: Sheet Steel Strength Data

Ultimate strength	44.8 (ksi)	Yield strength	17.8 (ksi)
Young's modulus	34638 (ksi)	Loading frequency	20 Hz
The axial loading mean	1300 (lb)	The axial loading amplitude	1300 (lb)

The entire class was divided into 4 teams. A detailed fatigue test procedure was provided to the students. Student teams were asked to measure the actual thickness and width of the specimen and follow the testing procedure to complete one fatigue test. The data was compiled in Table 2, which showed the fatigue loading conditions. Each team was asked to run one fatigue test, which lasted approximately 15 minutes. The teams all shared the test results to utilize for their analysis. The average of the fatigue cycle number of the 4 tests in Table 2 was compared to both theoretical hand estimation and FEA simulation results.

Table 2 the testing results with a loading frequency 20 Hz

Team#	The axial loading mean	The axial loading amplitude	Thickness (inch)	Width (inch)	Final fatigue life at failure
Team #1	1300 (lb)	1300 (lb)			
Team #2	1300 (lb)	1300 (lb)			
Team #3	1300 (lb)	1300 (lb)			
Team #4	1300 (lb)	1300 (lb)			
Notes: The fatigue life at failure at this stress level will range between 1000 cycle and 36900 cycles with the probability of 99.7 %.					

C: Exposure three: Fatigue FEA simulation of the fatigue life

Numerical simulation tools (FEA analysis) can be used to estimate the average fatigue life of the specimen. SolidWorks Simulation, which is the FEA module of the SolidWorks Platform, was used to run the fatigue FEA simulation analysis. In SolidWorks Simulation, the fatigue FEA simulation included two steps: (1) run the static analysis on the fatigue specimen by using the maximum loading and (2) run the fatigue damage simulation based on the stresses obtained in the static analysis of the fatigue specimen, which will be briefly explained in below.

- **Run the static analysis by using the maximum loading**

Since the sheet-type specimen during fatigue testing was gripped by the fixtures in the Instron 8801 fatigue test machine, the griped surfaces of the specimen in FEA simulation was simplified as the fixed surfaces. The bottom fixtures had a cyclic up-down motion driven by the hydraulic system. It was assumed that the shear gripping forces were applied to both gripped areas in the FEA simulation. The procedure for running the static analysis using SolidWorks Simulation [18] was provided and demonstrated during the laboratory session.

- **Run the fatigue damage FEA simulation**

The mean stress and amplitude of the loading cycle were determined using a static stress analysis. The axial cyclic loading during the test varied from zero force to a specified maximum tension force to avoid the rectangular tension test specimen buckling. Since our intended loading cycle would apply a load and then release to zero, the stress ratio R_s, which is defined as the minimum stress divided by the maximum stress is zero. The procedure for fatigue simulation analysis by SolidWorks Simulation [19] was provided to the students. A faculty demonstration of the procedure was conducted during the laboratory session. Before the fatigue FEA simulation was started, the students were required to calculate the fatigue strength reduction factor K_f, which includes all Marin modification factors [1].

The properties of the fatigue damage FEA simulation were set as shown in Figure 4: (1) there was no interaction among the cyclic stress; (2) the equivalent Von Mises stress was used for the cyclic stress and (3) the Goodman approach was used to consider the effect of the mean stress. Figure 5 shows the appropriate settings for a fatigue damage FEA simulation for the S-N curve derived from material Elastic Modulus based on ASME carbon steel curves [18].
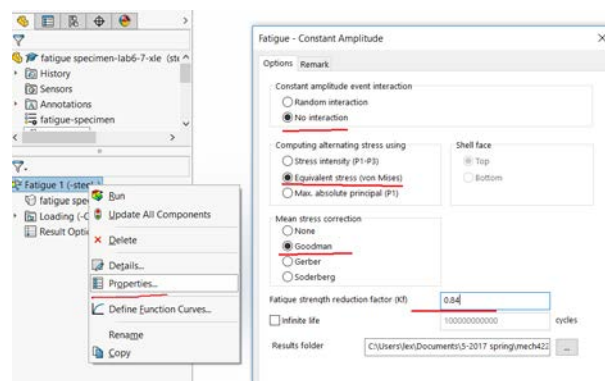

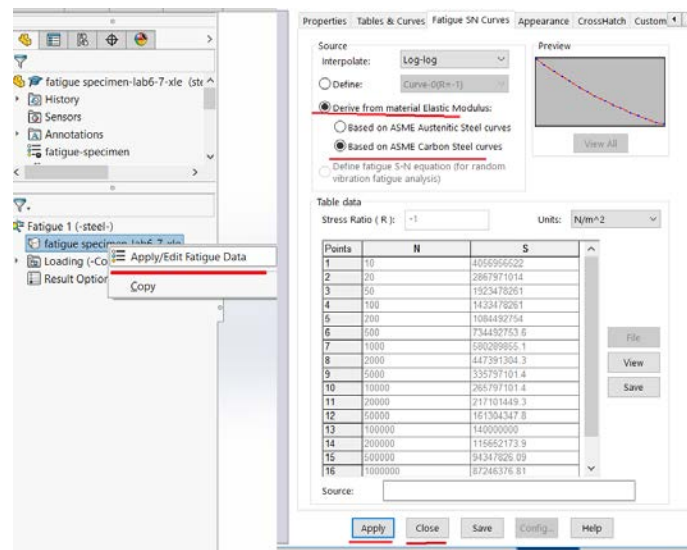Figure 4: Setting the "Properties" to enable fatigue simulation

Figure 5: Establishing the simplified S-N curve for the fatigue FEA simulation

The fatigue FEA simulation was used to estimate the average fatigue life of the fatigue test specimen. Each run utilized the test cyclic loading with a specific number of cycles which provided a fatigue damage percentage distribution plot as shown in Figure 6. When the fatigue damage percentage reaches 100%, it means that the specimen fails due to fatigue. Students were asked to run several simulations as outlined in Table 3. The fatigue damage percentages listed in the second column in Table 3 was cited from one student group report. Then students were asked to Microsoft Excel to estimate the number of cycles that causes 100% fatigue damage.
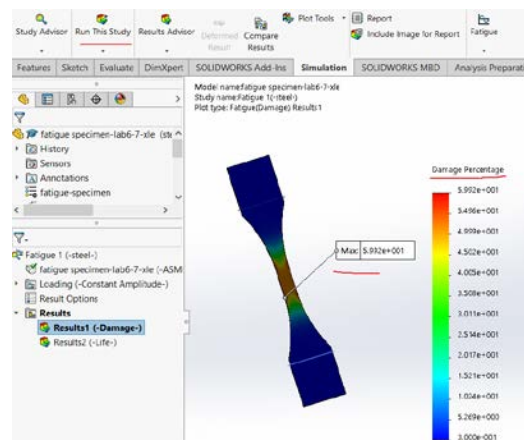

Figure 6: FEA plot of "Damage percentage"

Table 3: FEA prediction table number of cycles vs. the fatigue damage percentage

Number of cycles	Fatigue Damage percentage
3000	38.57
4000	51.14
4500	57.85
5000	64.28
5500	70.71
6000	77.13
6500	83.36
7000	89.99
7500	96.42
8000	102.8
8500	109.3

D: Exposure four: Theoretical calculation of the fatigue life and laboratory report

During lectures, students had been instructed on how to estimate the fatigue life of a component based on the simplified component S-N curves. These curves were adapted to obtain the application specific curves which utilized the base material ultimate strength and the Martin factors [1]. In calculating Martin factors, it was assumed that the fatigue test specimen was a "machined part". During the laboratory, students were required to develop the theoretical calculation to estimate the fatigue life of the fatigue test specimen for comparison to the FEA simulation of fatigue life and the fatigue life test results. Each team was required to develop a formal laboratory report which was submitted for grading.

3. Implementation, direct observations, and class survey results

The proposed integrated active learning approach was successfully implemented over the span of two weeks utilizing 4 lectures, 3 homework assignments and 2 laboratory sessions in the 2017 spring semester.

A: Observations on Exposure one: lecturing and homework assignment

Thru direct observation and discussion with students, it appeared they just treated the fatigue theory like other theories they had studied in other classes, expecting the theoretical calculations to match exactly with the experimental results. They did not grasp that actual fatigue failure of a component might not occur at an exact number of cycles. When predicting the fatigue life of components, many students still believed that they would get one value of the fatigue life by using fatigue theory.

B: Observations on Exposure two: Physical fatigue testing

During the physical fatigue test, a buckled fatigue specimen was demonstrated with the bottom fixture at a frequency of 20 Hz. After the demonstration, they had a vivid understanding of the cyclic loading and why the sample required a tensile fluctuating load only to avoid buckling. When they completed the fatigue test, they observed the specimen with multiple cracks as shown

in Figure 6. This provided a firsthand visual to help in understanding the fatigue damage mechanism.
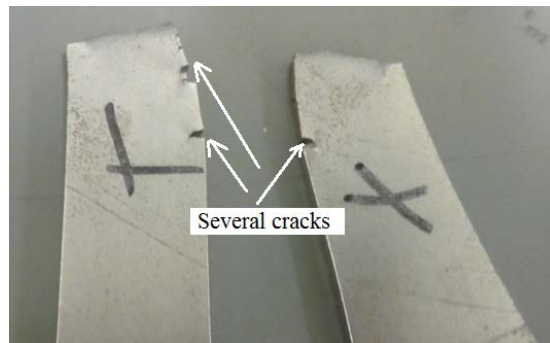

Figure 6 a fatigue test specimen with multiple cracks

During the physical fatigue test, each team only run one fatigue test. When a fatigue test was completed, the data was recorded on the whiteboard. The fatigue test results were shared for the entire class. The four fatigue test data during the laboratory are listed in Table 4. Students all asked why the test results were so different. Now, they started to understand that one of the defects of the component was randomly activated and developed to become the primary crack leading to fatigue failure. This caused the fatigue life of the same components under same cyclic loading to be different.   In Table 4, a note about the range of possible fatigue life of this sheet-type specimen was listed according to the 50 fatigue tests of the same specimen under the same loading conditions with a loading frequency 20 Hz.   During the laboratory, we mentioned that the fatigue life of this fatigue test specimen was in the range of 1000 to 36900 (cycles) with the probability 99.7 %, which was obtained from our actual physical fatigue test data.

Table 4 the testing results with a loading frequency 20 Hz

Team#	The axial loading mean	The axial loading amplitude	Thickness (inch)	Width (inch)	Final fatigue life at failure (number of cycles)
Team #1	1300 (lb)	1300 (lb)	0.602	0.098	8338
Team #2	1300 (lb)	1300 (lb)	0.604	0.100	8151
Team #3	1300 (lb)	1300 (lb)	0.602	0.100	8891
Team #4	1300 (lb)	1300 (lb)	0.606	0.100	2006
Notes: The fatigue life at failure at this stress level will be in the range 1000 cycle to 36900 cycles with the probability 99.7 %.					

C: Observations on Exposure three observations: Fatigue FEA simulation of the fatigue life

Using FEA simulation, students could visualize the distribution of percent damage caused by fatigue. Using FEA the students found that the fatigue damage results could easily be obtained for different cyclic loading.   To run the fatigue FEA simulation, students first calculated of the

fatigue strength reduction factor, set the simulation properties to conduct a fatigue simulation and then chose to utilize simplified S-N curves. All these activities were reinforced the implementation of the fatigue theory again. Students were able to conduct the analysis and easily develop data which was used in the final laboratory report.

D: Observations on Exposure four: Theoretical calculation of the fatigue life and laboratory report

The final exposure required theoretical calculation of the fatigue life for the test specimen. Students were required to implement fatigue theory, which was discussed and explained during the lectures, to estimate the fatigue life of the real specimen tested in the laboratory. This value was compared to both the FEA and testing results in the laboratory report. The student laboratory reports were well integrated and demonstrated a basic working understanding of fatigue concepts.

E: Student survey results

A class survey was conducted to obtain feedback regarding the new integrated active learning approach. The survey consisted of two questions. The first question was: "The fatigue laboratory including fatigue test, theoretical estimation, and FEA simulation facilitate me to have a better understanding of fatigue theory". The student was presented with 5 possible choices: strongly agree; agree; no opinion; Disagree, and strongly disagree.   The survey results are listed in Table 5. The 66.7 percent of students strongly agreed, and the 33.3 percent of students agreed that the integrated approach with a fatigue laboratory which included a fatigue test, theoretical estimation, and FEA simulation facilitated their understanding of fatigue theory. That is, 100 percent of students all agreed or strongly agreed to the statement.

Table 5 the class survey data on the class survey question 1

Choice	Response	Percentage
Strongly agree	10	66.7%
Agree	5	33.3%
No opinion	0	0%
Disagree	0	0%
Strongly disagree	0	0%

The second question in the class survey was "Any comment".   The comments collected strongly supported the integrated active learning approach. The following were some comments from the survey:

- "I like how we were able to see how the testing was actually done. This laboratory helped relating the FEA and hand calculation to real-life failure."
- "Being able to see in person how fatigue works and what it looks like as it fails helped a lot."
- "I find that comparing physical demonstration results to theoretical estimation better my understanding of how theory can be applied."

- "It is nice to be able to visualize how the data was obtained for these types of tests. And also, be able to compare theoretical calculations with real-life data."
- "This laboratory allowed us to see the type of cyclic stress, understand why we need to modification factors, and demonstrated how hard it really is to get a good estimation of fatigue life since some samples broken at 2000 cycles while others lasted until 8000 cycles. "
- "Being able to visually see the test, calculate the theoretical results and simulate it in SolidWorks give you a good grasp of fatigue."
- "The experiment facilitated the understanding of how to find the fatigue cycle of a specimen theoretically and experimentally. The laboratory provides a visual to the theory learned in lecture. "
- "The SolidWorks FEA gives us a more practical understanding of failure theory and how it might be evaluated in the workplace. It also offers a good starting point for cyclic loading, one of the hardest and most time-consuming experiments to collect data for in the laboratory."
- "Theoretical, simulation and actual test have different approaches to learning and doing all of them make a lot helpful to learn."

4. Discussion and Conclusions

Fatigue theory can be taught through a traditional approach in which fatigue theory is lectured and implemented in homework assignments. However, since the concepts of fatigue damage and failure are very complicated, some students might not develop a basic working understanding of fatigue theory in the typical two weeks of time allotted in an undergraduate curriculum. In our experience, the lack of fully grasping the concepts of fatigue caused some students to avoid fatigue-related analysis in their senior mechanical design projects.

To facilitate students developing a better working understanding of fatigue theory, we proposed the integrated active learning approach for teaching fatigue theory, which included lecture & homework, physical fatigue specimen testing, fatigue FEA simulation and theoretical calculations. The proposed approach was successfully implemented in the spring semester of 2017. 100% of students supported the proposed approach and agreed that it facilitated their development of a better working understanding of fatigue theory. Based on our observations, conversation with students, and comments in the class survey, the physical fatigue testing, and the fatigue FEA simulation really helped students to grasp the basic concepts of fatigue theory. We believe the experience will help them implement fatigue theory in their future mechanical designs.

5. References

[1] Ralph I. Stephens, Ali Fatemi, Robert R. Stephens and Heney O. Fuchs, "Metal fatigue in engineering," second edition, New York: J. Wiley, 2002
[2] Norton, Robert L, "Machine Design: An Integrated Approach," Second edition, Upper Saddle River, New Jersey: Prentice-Hall Inc, 2000

[3] Richard Budynas and Keith Nisbett, "Shigley's Mechanical Engineering Design," 10th Edition, New York, NY: McGraw-Hill Education, 2015

[4] Le, X., & Olia, M., & Moazed, A., & Roberts, R. L. (2016, June), *"Design a New Set of Strength Labs for the Course, 'Mechanics of Materials',"* 2016 ASEE Annual Conference & Exposition, New Orleans, Louisiana, June 2016

[5] M. Budhu, *"Virtual Laboratories for Engineering Education",* Proceeding of International Conference of Engineering Education, Manchester, UK, August 18-21, 2002.

[6] P. Bhargava1, C. Cunningham, M. Tolomeo, and A. Zehnder, *"Virtual Labs, Real Data for Statics and Mechanics of Materials"*, ASEE 2003 Annual Conference, Nashville, Tennessee, June 2003,

[7] Dues, J., & Le, N., *"High Cycle Fatigue Tester*," 2006 ASEE Annual Conference & Exposition, Chicago, Illinois, June 2006

[8] Sepahpour, B., *"A Practical Educational Fatigue Testing Machine,"* 2014 ASEE Annual Conference & Exposition, Indianapolis, Indiana, June 2014

[9] Fleming, D. C., *"A Fatigue Life Experiment for Aerospace Engineering Undergraduates,"* 2016 ASEE Annual Conference & Exposition, New Orleans, Louisiana, June 2016

[10] J. Zecher, *"Teaching Finite Element Analysis in a MET Program*", ASEE 2002 Annual Conference, Montreal, Canada, June 2002

[11] W. Howard, T.J. Labus, and V.C. Prantil, *"Combining Computer Analysis And Physical Testing In A Finite Element Analysis Course*", ASEE 2004 Annual Conference, Salt Lake City, Utah, June 2004

[12] Le, X., & Moazed, A. R., & Duva, A. W., *"The Design Projects for the Simulation-Based Design Course,"* 2016 ASEE Annual Conference & Exposition, New Orleans, Louisiana, June 2016

[13] Hagigat, C., *"Using Commercially Available Finite Element Software For Fatigue Analysis,"* 2005 ASEE Annual Conference, Portland, Oregon, June 2005

[14] Brown, A.O., Rencis, J.J., Jensen, D.A., Chen, C.C., Ibrahim, E., Labay, V., and Schimpf, P., *"Finite Element Learning Modules for Undergraduate Engineering Topics using Commercial Software,"* 2008 ASEE Annual Conference & Exposition, Pittsburgh, PA, June 2008.

[15] Brown, A. O., & Rencis, J. J., & Jensen, D. D., & Schimpf, P. H., & Crawford, R. H., & Orabi, I. I., & Watson, K. A., & Liu, J., & Jackson, K. S., & Bhattacharyya, M., & Webster, K. L., & Chen, C., & Akasheh, F., *"Active Engineering Education Modules: Summary Paper of Five Years of Incremental Improvements to the Modules,"* 2016 ASEE Annual Conference & Exposition, New Orleans, Louisiana, June 2016

[16] ASTM STM E466 – 15, Standard Practice for Conducting Force Controlled Constant Amplitude Axial Fatigue Tests of Metallic Materials,

[17] Le, X., & Roberts, R. L., & Connors, H., & Saykin, V. V., & Alhuwayrini, M. K. *"The Sagan Research Project for Exploring Statistical Parameters of Typical Mechanical Properties,"* 2017 ASEE Annual Conference & Exposition, Columbus, Ohio, June 2017

[18] Pau Hurowski, *"Engineering Analysis with SOLIDWORKS Simulation 2016,"* SDC publications, Mission, Kansas, 2016

[19] Dassault Systems SolidWorks Corporation, *"SolidWorks 2012-SolidWorks Simulation Hands-on Test Drive,"* Dassault Systems SolidWorks Corporation, 2012