Failure Analysis for Engineering Technology Students

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Introduction:

Mechanical engineers are often required to perform failure analysis on components that might have failed prematurely or unexpectedly. The process is complex and draws upon many different technical areas of mechanical engineering and requires engineers to accurately solve problems in those technical areas.

This paper presents how a failure analysis project is incorporated into a senior-level, undergraduate, material science course and the benefits to the students to employ knowledge gained in other courses to complete the analysis. The project is given as part of a laboratory exercise on failure (forensic) analysis. The project is given in lab following two lectures on failure analysis. The failure topics discussed in lecture include appearance of fracture surfaces, fatigue versus static failure, ductile versus brittle failure, corrosion, basic metallurgy and material selection.

The forensic analysis is a case study involving a 100 year-old, 18 ton, steam-powered, steel-wheeled tractor that experienced a boiler explosion that killed several people and injured scores of others at a county fairground. Students are presented with a basic problem definition and then work in groups of three determine root causes of the failure.

The project requires students to brainstorm, form a hypothesis, problem solve and then present their hypothesis, analysis and conclusions to their fellow students in the form of an oral presentation. Student performance is assessed by their appropriate use of strength of materials, finite element analysis, heat transfer, thermodynamics, material science (corrosion), and dynamics, since all of these areas must be employed to solve the problem. As a result of the exercise, students come to appreciate how various elements of engineering are coupled together to solve an engineering problem.

This is the second of two major semester capstone projects given in this senior level material science course. The emphasis of the first project, *Design Optimization Problem in a Materials Engineering Course*[1], is on design, material selection, and optimization while this project focuses more on analysis and requires the additional use of supplementary knowledge in the areas of thermodynamics, corrosion, and heat transfer.

Problem Definition:

Students are provided with a two-page executive summary containing details of the antique tractor explosion. The document summarizes operating conditions, bystander testimony, the sheriff's report, and testimony from various forensic engineering experts. The information provided in the executive summary is available in numerous on-line articles posted on various steam tractor websites[2,3]. Students are provided with these links and encouraged to review them. Students are also presented with several forensic photos of the actual tractor after explosion (Figure 1) and various micrographs depicting the fracture surface of the failed crown plate. Finally, several schematics and engineering drawings are provided to describe the failure and construction of the boiler (Figure 2). These figures clearly show the structural failure of the crown plate (top of firebox) which led to the boiler explosion.

Figure 1: Photo of Antique Tractor after Explosion[2]

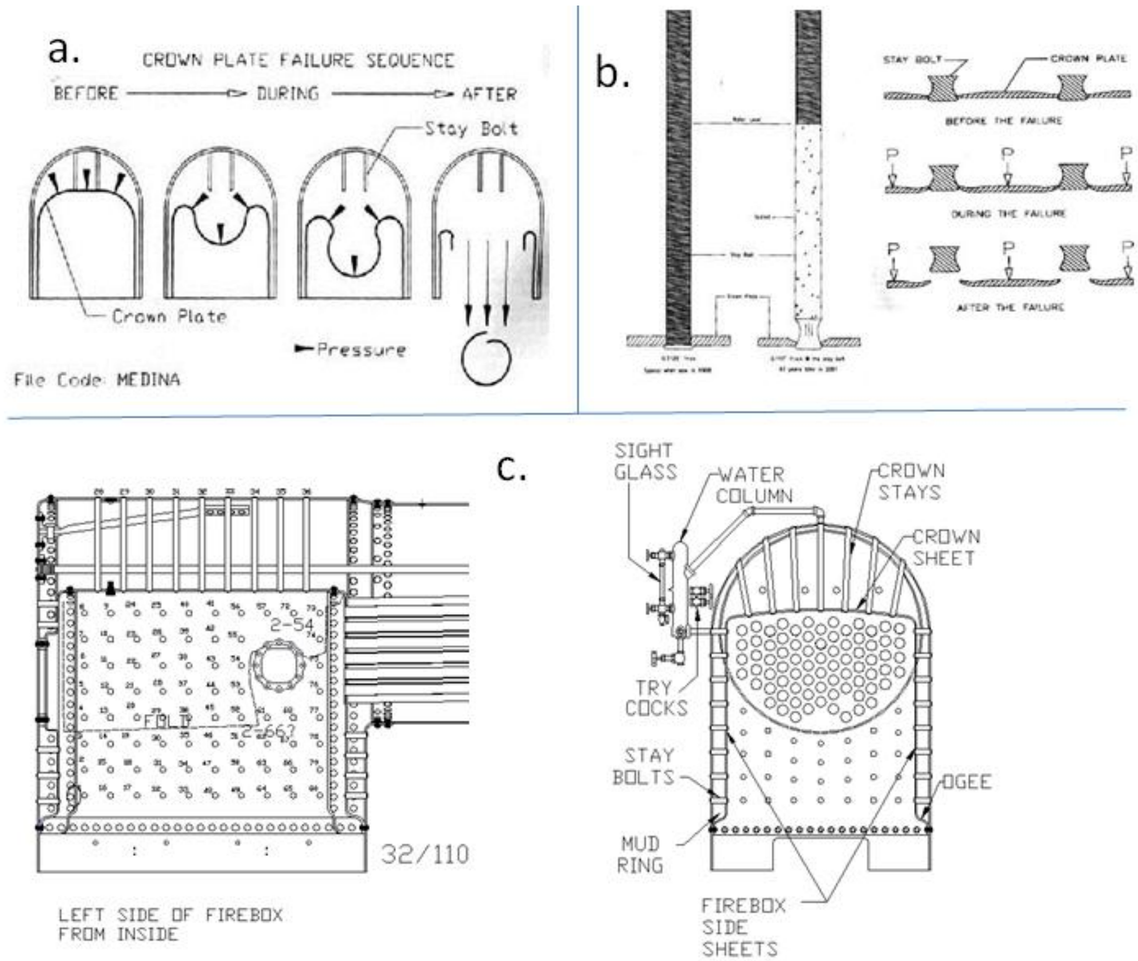


Figure 2: Various schematics and detailed drawings[2] are included in the executive summary including, a) sequence of failure for crown plate, b) corrosion details of stay bolts and crown plate, c) detailed CAD drawing showing the failure line where crown plate separated from firebox

Students, working in groups of three, spend an entire two hour lab reviewing the executive summary and various forensic reports. This is followed (usually a week later) by a general class discussion in which various likely failure scenerios are discussed. As a result of these discussions, it is theorized that the cause of failure may be a result of the following three scenarios:

- Scenerio 1: The physical failings of the engine were more at fault than possible operator error (insufficient water level). Forensic analysis on the crown sheet of the boiler showed significant corrosion which caused the crown sheet to uniformly thin from an initial thickness of 0.3125” thick to approximately 0.110” thick in some places. This was insufficient metal to hold the pressure of the steam, resulting in the mechanical failure of the crown plate. Additionally, one or more stay bolts may have failed prior to the explosion which would result in a reduction in crown sheet support. Under this scenerio, the crown plate might have failed even under normal operating pressures of the boiler (120 psi nominal to 200 psi max). The key with this scenerio is an understanding of corrosion and the likelihood that 90+ years of corrosion could have resulted in the crown plate corroding to approximately 35% of its original thickness.

- Scenerio 2: Improper water level caused the coal fire in the firebox to heat the exposed crown sheet to such a high temperature that the tensile strength was compromised. The crown sheet (nominally 0.3125" thick with a hardness of 88 HRB) failed under normal pressure in the boiler. The key with this scenerio is the high temperature effect on steel.
- Scenerio 3: The coal fire in the firebox again heated the exposed crown sheet to a high temperature. When the tractor jerked, liquid water back onto the very hot crown sheet, the liquid flashed instantly into super-heated steam producing a pressure in excess of the relief valve pressure, rupturing the hot and weakened crown sheet, blowing through the firebox, rocketing the tractor upward 15 feet and breaking the firebox and parts of the lower boiler into small pieces of steel, sending them flying like shrapnel. The key with his scenerio is flashing of water into superheated steam which creates pressures well above the maximum allowable operating pressure.

Students then spend the next several weeks performing analysis to substantiate these claims. Each student has responsibility for a certain aspect of the analysis and works with other team members to postulate final conclusions.

Analysis:

Figure 3 shows the various elements of engineering that come into play and how they are coupled together to impact the problem at hand. Of primary importance is the structural analysis. Various forensic reports, reviewed by the students, clearly detail the condition of the crown plate after the explosion[2,3] and point to its weakened state before the explosion as a primary cause of failure.

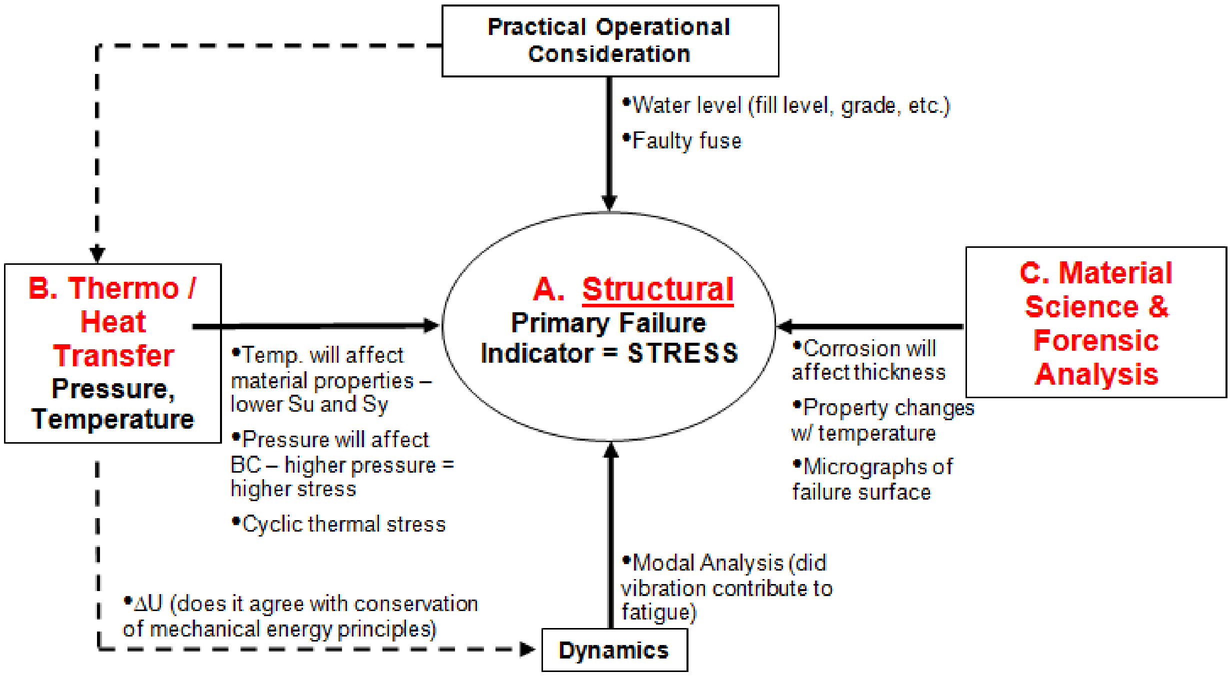


Figure 3: Coupling of Engineering Fundamentals. Working in groups of three, each student picks a focus area (A, B or C).

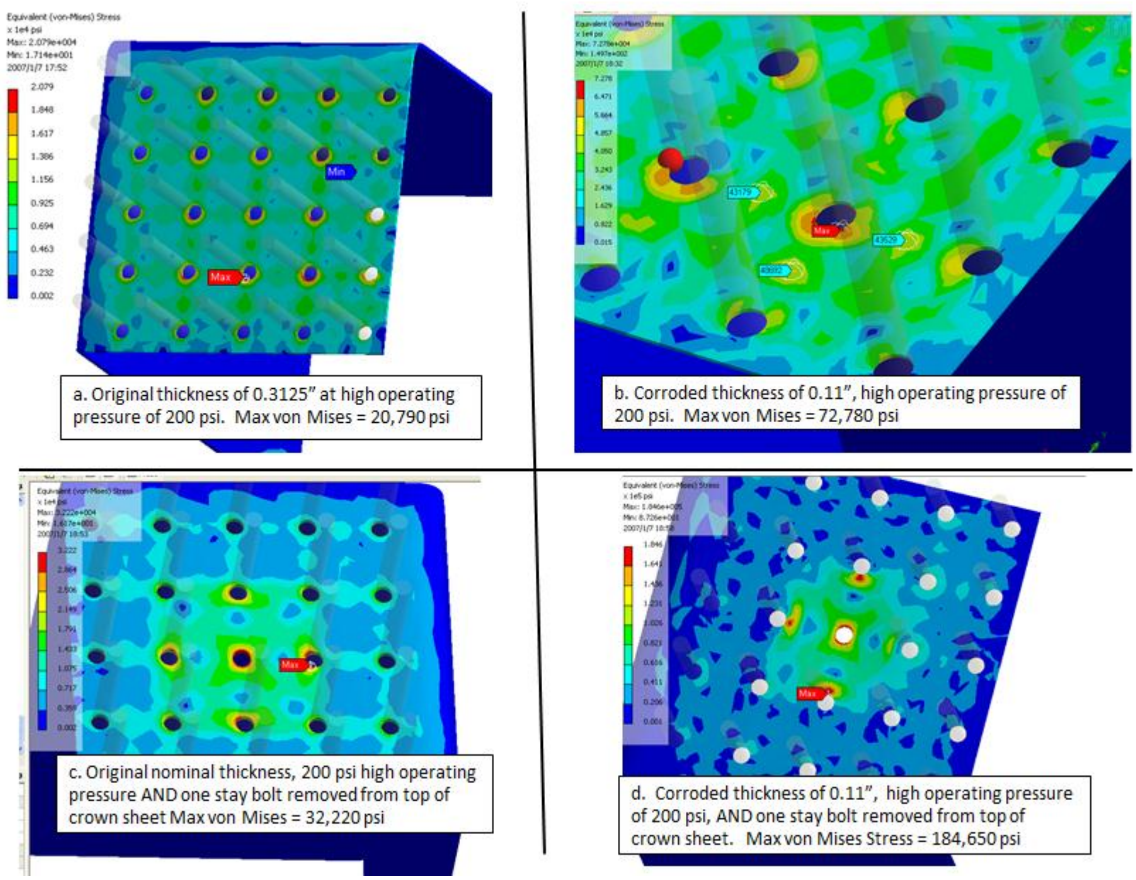
The primary failure mode for each of the failure scenerios described above is structural failure of the crown plate. Thermodynamic and heat transfer also come into play to understand how the crown plate might have heated up with possible pressure spikes due to flashing of water on the crown plate. Finally, various material science aspects come into play to better understand the corroded nature of the crown plate, various micrographs of the failure and how high temperaure impacts the mechanical properties of steel. All aspects of engineering shown in Figure 3 are necessary to adequately reach conclusions. Working in groups of three, each student takes on the responsibility of either performing the strucural analysis, thermo analysis, or investigating the material science aspects. Students meet as a group continously over the course of several weeks sharing their findings so a final report can be created together. Responsibilities are typically broken down as follows:

Student "A": Structural Analysis:

This student performs FEA (finite element analysis) on the crown plate. Regardless of what step is performed first (thermodynamics or heat transfer), the structural analysis must be completed since the primary failure mode is structural failure of the crown plate. The geometry of the crown plate is well defined based on drawings and actual field measurements. This student performs various FEA studies on the crown plate at various pressures including:

- 120 psi = low operating pressure
- 200 psi = maximum operating pressure
- 250 psi = estimated to be the maximum pressure the tractor was operating at prior to the accident.

Analysis typically includes the crown plate at original thickness (0.312"), corroded thickness (0.11") and with a stay bolt missing. Typical results are shown in Figure 4.



a. Original thickness of 0.3125" at high operating pressure of 200 psi. Max von Mises = 20,790 psi

b. Corroded thickness of 0.11", high operating pressure of 200 psi. Max von Mises = 72,780 psi

c. Original nominal thickness, 200 psi high operating pressure AND one stay bolt removed from top of crown sheet Max von Mises = 32,220 psi

d. Corroded thickness of 0.11", high operating pressure of 200 psi, AND one stay bolt removed from top of crown sheet. Max von Mises Stress = 184,650 psi

Figure 4: Analysis results for failed crown plate at 200 psi boiler pressure, a) original thickness, b) corroded thickness, c) original thickness and one stay bolt missing, d) corroded thickness and one stay bolt missing.

The analysis shows failure of the crown plate for the following two cases: corroded thickness (b) and at the corroded thickness with one stay bolt missing (d). So, regardless of the thermo aspects of the problem (improper water level), structural failure of the crown plate could have occurred due to the poor condition of the boiler prior to the explosion. Students typically perform FE analysis on the cases shown in Figure 4 as well as many other cases and summarize the results in a table.

The student responsible for the structural analysis is also asked to verify FEA results with closed-form calculations wherever possible. For example, plate theory[4] shows the maximum normal stress, S, around a hole can be calculated using:

$$S = \frac{qRo^2 F_7}{t^2}$$

Where q = applied pressure, Ro = outer radius, t = plate thickness and F_7 is a stress factor based on the geometry of the plate.

In addition to hand calculations, the student responsible for the structural analysis (student "A"), is asked to defend the accuracy of his or her FE analysis. Students are encouraged to report structural error and explore submodeling techniques on the crown plate. For example, Figure 5 shows submodeling on the crown plate a student performed to validate the accuracy of his FE model. Figure 4.a. is a refined sub model containing 80,000 solid elements while Figure 4.b. is the original analysis with 11,000 elements. Both models are in agreement with a maximum von Mises stress of 12 ksi at the hole.

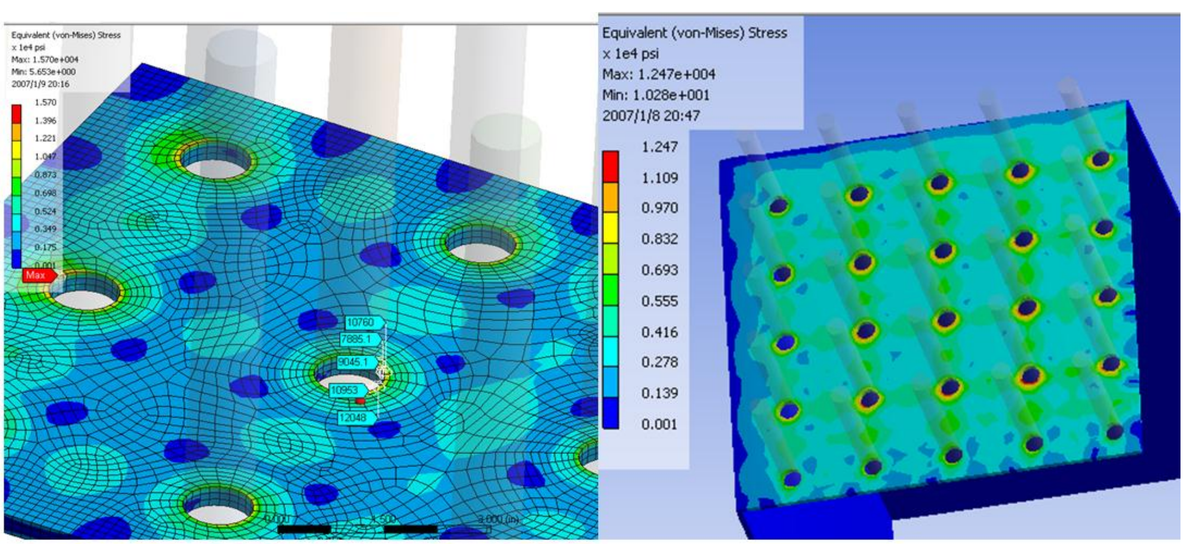


Figure 5: Submodeling used to validate the accuracy of a students FE analysis, a) submodel containing 80,000 solid elements and, b) shell model contating 11,000 elements. Results shown are for the benchmark case (original 0.312" thick crown plate and 120 psi boiler pressure).

Student "B": Thermodynamic and Heat Transfer Analysis:

There is strong evidence in the forensic reports that suggests the crown plate heated up beyond normal operating conditions prior to the explosion. The top of the firebox (crown plate) is always exposed to severe heat but as long as it is covered with water, the temperature will be approximately equal to the water temperature at operating pressure since the heat transfer coefficient dominates the heat transfer system. However, when the water level drops below the crown plate, the crown plate is in contact with super-heated steam which has a lower convection coefficient and consequently the temperature of the plate will rise. Additionally, the boiler exploded while the tractor was backing up suggesting water splashed on the "hot" crown plate and instantly flashed into steam. As the water instantly flashed into steam, a pressure spike could have occurred.

The job of student "B" therefore is to investigate the thermo aspects of the problem as described in the preceeding paragraph and further detailed in senerio "B" and "C" described above. This student is required to perform a heat transfer analysis on the boiler which is used to determine that the crown plate could indeed reach temperatures of up to 900^{o}F if exposed. Additionally, thermodynamic analysis is used to show that pressure spikes of 1,200 psi can be achieved if water splashes onto the crown plate and is instantly vaporized into superheated steam.

Student "C": Material Science Aspects

This student is responsible for examining the numerous forensic photos and reporting findings on type of fracture, condition of failed components, etc. Course notes,course text[8] and other sources[5,6,7] are used as references. This student also performs a corrosion analysis to verify the corroded condition of the boiler. Finally, this student is responsible for investigating how mechanical properties of the crown plate might be impacted by temperature. The student refers to an earlier lab exercise where various steel alloys were tensile tested at various temperatures as well as other references[9].

Technical Forensic Analysis Conclusions:

After each student completes his or her portion of the analysis, final group meetings are held in which the students formulate final conclusions. These conclusions are usually broken into the three main categories: structural analysis, thermo analysis and material science analysis. Typical conclusions can be stated as follows:

Based on Structural Analysis:

1. The corroded thickness case of 0.11” is not safe at any of the pressures considered (120, 200, 250 psi) based on distortion-energy theory. Based on a factor of safety of two, the maximum pressure that could be safely used for the corroded condition is approximately 50 psi.
2. The benchmark case of nominal thickness of crown plate as new (0.312”) is safe and meets PV code requirements at pressures up to 200 psi.
3. For the corroded case at pressures above 200 psi, failure was almost imminent with failure being predicted at 250 psi based on the actual estimated tensile strength!
4. With just one stay bolt missing, stress more than doubles. Considering the corroded condition with one stay bolt missing, failure would have occurred at 100 psi pressure.

Based on Material Analysis:

1. The crown plate’s (A36 medium carbon steel) strength is greatly influenced by temperature and starts to decrease at temperatures above 500˚F with a 10% decreases at 700^{o}F, 21% decrease at 900^{o}F, etc.
2. Given the material, environment and 90+ years of service, it is highly likely that the crown sheet could have corroded from 0.312” thickness to 0.110” thickness.

Based on Thermo/ Heat Transfer Analysis:

1. The crown sheet could have easily reached temperatures of 900^{o}F with crown the sheet exposed. If the steam turned to superheated, pressures between 195 psi up to 400 psi could have resulted.

2. The exposed crown sheet could have vaporized at least 5 lbs of water which could have resulted in pressures of 690 psi up to 1,200 psi!

In addition to the technical aspects of the forensic analysis, after the completion of the project, students have a great appreciation for how complex real-world forensic problems can be and the many aspects of mechanical engineering that must be used. They also appreciate the importance of working in groups and how each member must become an expert in his or her portion of the analysis so the whole group can be succesful.

Grading Rubric for Final Presentation:

- Introduction and Adequate Problem Definition………..10 pts
- Hypothesis (Failure Scenerios)…………………………10 pts
- Technical Content……………………………………….50 pts
    - Student "A" Structural analysis
    - Student "B" Thermo Analysis
    - Student "C" Material Analysis
    - Entire Group Technical content
- Conclusions…………………………………………….20 pts
- Quality of Presentation…………………………………10 pts
- Total……………………………………………………100 pts

Student Feedback

At the completion of the project, the students were given a survey to gain insight on their thoughts about the project. All 34 students completed the survey. The following shows the survey questions and the student's responses:

1. Q: The forensic project was interesting?
   Student Response: Likert Scale 6.3/7.0
2. Q: The level of complexity of the forensic project was adequate for this couse?
   Student Response: Likert Scale 6.1/7.0
3. Q: The forensic project's educational value was high (i.e. you learned a lot)?
   Student Response: Likert Scale 5.9/7.0

4. Q: You feel that this project, or another forensic project, should be included in this course for future students?

   Student Response: Likert Scale 5.8/7.0
5. Q: What changes would you make to the forensic project?

   Summary of student responses: The change suggested most by the students was to allow more time to complete the project. A couple of suggestions were made to make the project less thermodynamic intensive and more structural.
6. Q: The MS PowerPoint presentation given to you by your instructor fully explained the project?

   Student Response: Likert Scale 6.2/7.0
7. Q: Comment on the Executive Summary and various forensic reports that were used to explain the project (i.e. level of adequacy, thoroughness, informative, etc...).

   Summary of student responses: The majority of the student's responses were they felt the project was adequately defined. A couple students suggested having example parts and more practice with the calculations prior to beginning the project.
8. Q: You enjoyed the challenge of the forensic project?

   Student Response: Likert Scale 5.9/7.0
9. Q: Which course or engineering topic did you rely on most to solve the forensic project?

   Summary of student responses: The course mostly used by the students was Finite Element Analysis (FEA). The secondary course used was Sstrength of Materials.
10. Q: Did you get the grade you thought you were going to receive?

    Student Response: Likert Scale 7.0/7.0
11. Q: If you did not get the grade you thought you were going to get on the assignment, why do you think you didn't?

    Summary of student responses: Students overwhelmingly stated that the project was adequately and appropriately graded. Not one student felt the grading was not adequate or inappropriate.

Conclusion:

Based on the work performed by the students and the student feedback, this project was found to be very appropriate, and rewarding for the students. It gave the students the opportunity to couple different engineering problem solving skills to correctly solve for the cause of the failure versus performing an analysis employing one engineering topic, and that is the uniqueness of the project. Other than capstone courses, which there are few in the four year curriculum, students are not challenged to solve engineering problems that require more than one engineering topic. This project serves as a precursor to prepare the students for the completion of their senior design projects.

Another benefit of this project is its ability to satisfy the Accreditation Board For Engineering and Technology (ABET) student outcomes. ABET designates the student outcomes as a through k. The following ABET student outcomes could be satisfied with this project:

a. An ability to select and apply the knowledge, techniques, skills, and modern tools of the discipline to broadly-defined engineering technology activities;

b. An ability to select and apply a knowledge of mathematics, science, engineering, and technology to engineering technology problems that require the application of principles and applied procedures or methodologies;

e. An ability to function effectively as a member or leader on a technical team;

f. An ability to identify, analyze, and solve broadly-defined engineering technology problems;

g. An ability to apply written, oral, and graphical communication in both technical and non-technical environments; and an ability to identify and use appropriate technical literature;

i. An understanding of and a commitment to address professional and ethical responsibilities including a respect for diversity;

k. a commitment to quality, timeliness, and continuous improvement.

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