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A First-Year Drilling, Tapping and Thread Stripping Exercise

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Abstract

This paper discusses the development, implementation and assessment of a drilling, tapping and thread stripping exercise used in an introduction to engineering course. The exercise was designed to be a time efficient way to improve hands-on skills that exposed students to various mechanical engineering concepts such as moments, yield strength, safety factor and fastener strength. The thread stripping apparatus involved a lever arm used to pull eyebolts out of the students' tapped holes in aluminum and ABS while measuring the force applied. Yield strength results from this simple apparatus compared favorably with results from a hydraulic tensile tester. Surveys of first year engineering students revealed that upon coming into the program only 28% of the students had experience with tapping a hole and the average student judged their comfort with hand tools as 7.1/10. End of course surveys revealed that average student comfort with hand tools was raised to 8.6/10 and 94% of students were confident in their ability to drill and tap a hole on their own. The exercise has been iteratively improved over two semesters and the details of the curriculum, lab exercise and physical thread stripping apparatus are provided as well as major lessons learned and suggestions for improvement.

Introduction

First-year engineering curriculum can potentially cover an incredible array of topics. Inevitably an instructor must prioritize the topics and depth of coverage as they best see fit. This prioritization becomes of increasing importance in classes which involve students from multiple engineering disciplines as well as classes which are shorter than the more common four credit introduction to engineering class. At the University of St. Thomas introduction to engineering is a 1 credit course which has both electrical and mechanical engineering students and is comprised of a 100 minute lecture and a 100 minute lab that meet each week during a 14 week semester. The curriculum is heavily geared towards project-based and hands-on learning with a goal of exposing students to many facets of engineering.

There are many works out there which show that students, and specifically first-year engineering students, learn by doing and retention can be improved by incorporating hands-on projects and exercises[1-4]. However, one challenge that can limit the effectiveness of these projects is the fact that many students are not confident with tools. In a curriculum requiring much building of projects this is a problem; students may be able to envision great products only to be overwhelmed when attempting to fabricate. Knowledge of tool use can lead to designs that can be built more easily, better understanding of the time required, and potentially more design iterations as there may be less time lost to tool training or uncertainty in the shop. In an industrial setting confidence with tools can additionally result in higher utility of an engineer in the fabrication, development, and maintenance of test set-ups.

There are a number of additional motivations for instructing first-year engineering students in tool use. First, there are significant numbers of incoming first-year engineering students who have little experience with hand tools, or have been so far removed from any training they might have received during K-12 that their comfort remains low[5-7]. Second, this deficiency can present safety and liability issues as tools are often made available to undergraduate students regardless of their ability. Moreover, Pappas and Prins[6] assert that critically thinking about a project and then physically constructing the project fosters more effective thinking and ultimately better designs. Thus, tool use combined with a design process has a larger positive learning outcome. Finally, these authors surmise that hands-on projects are beneficial to students whose engineering interests lie elsewhere as the act builds a general procedural knowledge that spans disciplines[7].

In order to help improve, or reinforce, tool use and cognitive skills on design and build projects Pappas and Prins[6-7] describe successful results from a studio "boot camp" wherein students receive formal training and practice with tools while completing hands-on exercises. In its inception, the project described in this paper expanded from the example set by their boot camp though was more limited in both scope and time. In addition to the hands-on laboratory experience this project also involved a classroom component to tie the act of drilling and tapping to an understanding of thread strength. The goals of this experience were to:

- develop a time efficient exercise in which students learn to properly drill and tap a hole
- instruct students on thread strength calculations
- compare thread strength calculations with experimentally determined results
- expose students to material to be further explored in later courses including moments, safety factor, and material properties

This paper describes the results of this experience as well as the experimental apparatus developed and lessons learned through multiple iterations.

Laboratory Experience

Each lab section for the class had ~15 students and was staffed by the course instructor and two undergraduate student mentors. These paid student mentors were typically sophomore or junior engineering majors who had received a quick refresher lesson on drilling and tapping. The introduction to engineering space was in a separate building from the main engineering department facilities and included a large classroom and laboratory space stocked with hand tools. At the start of the 100 minute lab session all 15 students were given a 10-15 minute lesson which included the following topics:

- description/definition of a bolt, machine screw and stud
- description of bottoming, plug, and taper tap and when they are used
- description of thread pitch and major diameter
- introduction to a drill/tap chart and how to use it
- description of hand drill parts and operation
- description of drill press parts and operation
- introduction to thread strength equation and material yield strength
- discussion of safety factor

- practice calculation of thread strength
- proper safety procedures

After this introduction the students were split into two groups of 7-8 students each. One group was given a 15-20 minute student mentor led tour of the machine shop, tool crib, wood shop and student work space. The objective of this tour was to show students the various resources they will have at their disposal for building projects as they progress towards their degree. They were also informed on when they would have access to the resources and who to talk to about being trained in on equipment.

The remaining 7-8 students were taken to the first-year design space where proper drilling, tapping, band-saw, safety, and clean-up procedures were demonstrated. At the end of the demonstration students were distributed to various work stations, each of which included:

- hand drills
- center drill bits
- tap handles
- ¼-20 taps
- ¼-28 taps
- ¼-20 bolts
- ¼-28 bolts
- assorted drill bits
- calipers
- scrap wood
- C-clamps

Before students could start their drilling/tapping exercise they each needed to use the band saw to cut a 4" long piece of aluminum and ABS. The aluminum used (McMaster.com part # 89755K27) was 1" wide and 1/8" thick. The ABS used (McMaster.com part # 8712K111) was 1" wide and ¼" thick. These materials were carefully chosen so that the threads would fail at a reasonable force which could be safely applied using the apparatus described later in this paper.

To practice drilling and tapping the students drilled 4 holes into the aluminum and ABS (8 holes total). Half of the holes were hand drilled and half were made using a drill press. Half of the holes were tapped ¼-20, half were tapped ¼-28 and students were asked to label each hole appropriately using masking tape for future use. These eight different conditions allowed analysis of thread strength performance differences to be made based on material, drilling technique and thread pitch during the following classroom component.

When the students on the tour returned the two groups switched positions. By splitting the group in half, the lab space was less crowded when students were first learning to drill and tap, allowing for greater oversight and assistance to those who appeared uncomfortable. Pappas and Prins[6] have suggested that for tool instruction four to six students per instructor is appropriate. By having the instructor and a student mentor able to assist the 7-8 students as they first practiced this ratio provided sufficient oversight. When the second tour ended the entire group of 15 students was working in the lab together while finishing their 8 holes. About 15% of students finished their holes well before the end of lab and were invited to see the thread stripping apparatus in action with the assistance of a student mentor. The other 85% of students typically finished 6-8 holes by the end of the lab period. In the interest of time, students who did not complete all 8 holes were not penalized or asked to complete them at a later time.

Thread Stripping Apparatus

In an early iteration of the project students were asked to use the thread stripping apparatus to break all their threads while recording the results. It was determined that this took too long and required most students to return outside of their lab time to complete the assignment. This was considered a problem for two reasons: 1. this course is 1 credit and the amount of work is a common criticism; 2. it was believed that after seeing one or two threads fail little was being learned by the students. In the most recent iteration all students got to see a single thread fail per lab section. The student mentors then collected the students' labeled holes and proceeded to strip the threads outside of class. This allowed for a collection of thread failure results to be produced without requiring each student in the class to find additional time to devote to the exercise.

The goals of the thread stripping apparatus developed for this exercise were:

- safely apply a continually increasing force to the point of thread failure
- measure the force applied at the point of thread failure
- be able to repeat tests and change samples quickly
- be able to be stored easily when not in use
- produce results that agreed reasonably well with more sophisticated equipment

The apparatus shown in Fig.1 is the result of three iterations. A 13.33:1 lever arm was used to amplify the forces actually applied to the threads. This allowed for a discussion of force moments in class and resulted in much smaller and safer forces for thread failure. One major lesson learned during the first iterations was that a 2" x 2" square steel tubing lever arm elastically deformed too much, but 2" x 3" tubing had sufficient rigidity. It was also determined that simply adding weights and removing them took a significantly more time than the shown configuration which incorporates a winch.

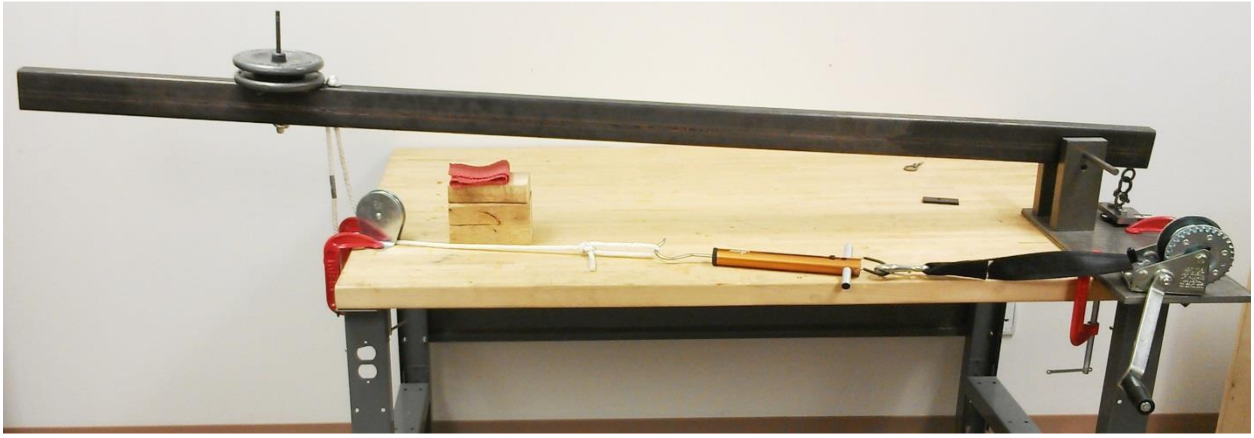

Figure 1. Thread stripping apparatus

In Fig. 1 it is shown that a winch is connected to a spring scale (Fig. 2a, oldwillknotscales.com, Weston Sportsman's 100#) that is then connected to one end of a lever arm by a rope which is turned through a pulley. This scale has a sliding marker which remained at the point of highest deflection when the threads actually failed thus allowing the failure force to be recorded. The other end of the lever arm incorporates an eye bolt which is threaded into a student-tapped hole

(Fig. 2b). The weight plates shown in Fig. 1 were added when stripping the aluminum threads as the force gage would have otherwise been maxed out at 100 lbf and not captured the actual failure force which was slightly higher. The initial angle of the lever arm can be adjusted by changing the height of the eye bolt screwed into the hole and/or by adjusting the eye bolt which is mounted to lever arm (Fig. 2b). This angle is of relevance because in the ideal scenario the lever arm would be horizontal (i.e. rope pulling at 90^o to arm) at the point of failure.

a.

b.

Figure 2. a) spring scale; b) eye bolt connection and restraint

To strip the threads the following procedure was used:

1. Use a wooden block to prop lever arm up.
2. Insert sample under restraint bar and between the bolts (Fig. 2b). Align the threaded hole with the hole in the steel restraint bar. Tighten restraint bar bolts.
3. Screw eye bolt into the threaded sample.
4. Shackle the eye bolt in the sample to the eye bolt on the lever arm. Raise the eye bolt on the lever arm by tightening the nut inside the level arm (Fig. 2b) so that the connection between the eyebolts and shackle is taught.
5. Remove wooden block supporting lever arm.
6. Tighten winch slowly until threads fail.
7. Record maximum lbf reading on gauge (Fig. 2a).
8. Slacken winch and replace wooden support block.
9. Remove eye bolt from shackle. Clean off threads.
10. Loosen bolts on restraint bar. Slide sample to next threaded hole. Repeat from step 2.

The above series of steps could be done by a single student mentor in ~ 2 minutes after a small amount of practice. Thus, the collection of experimental thread failure results could be done in a more reasonable amount of time and much more efficiently than having all students in the course trained on how to use the apparatus and then measure the failure force of their 8 holes. In Fig. 1 a block of wood is seen resting on the table near the pulley which prevents the lever arm from hitting the pulley when the threads fail. There are a few metal parts that bang together when the threads fail using this apparatus which can be a little startling to people nearby, though the noise is not so loud as to be dangerous. C-clamps were used to hold the pulley and apparatus to the table, which proved sufficient and thus precluded the need to mount the system to the table by more destructive means such as putting bolts through the table. The entire set-up could be stored quickly and easily by simply undoing the C-clamps and sliding the bar on which the arm pivots out from the two support posts. This apparatus is relatively affordable and simple to construct. More details are found in the Appendix.

Lecture Activity

The lab activity was tied into the lecture component of the class as well. During lab periods subsequent to the drilling/tapping exercise, student mentors used the thread stripping apparatus to test the student made threads to failure. As each hole was labeled, a comparison could be made between the different materials, thread pitch, and drilling technique. During lecture students were asked to calculate the expected force at which their threads should fail as well as the expected force being supplied by the winch. The goal of this was to introduce moments and revisit the concept of yield strength and the thread force equation which were first introduced at the start of the lab exercise.

To predict the force at which the threads would fail the following equation was used:

$$\mathrm{F}_{\mathrm{predicted}} \approx \pi \cdot d(0.75t)(0.58S_y) \qquad \textbf{Eq. 1}$$

In Eq. 1 the major diameter is d, the material thickness is t, and the material yield strength is S_y. If the yield strength of the material is known one can predict the force that the threads can hold. Because the eye bolts used were made of steel, which has a relatively larger yield strength, the tapped aluminum and ABS threads failed before the eye bolt threads.

To determine the winch force, one considers that just before failure the moments on the short and long side of the lever are in balance as in Fig. 3. The downward force (F_{down}) is comprised of the weight of the bar and any weights measured at L_1 plus the force with which the winch is pulling as read by the spring scale. Thus the actual failure force on the threads could be calculated as:

$$\mathrm{L}_1\mathrm{F}_{\mathrm{down}} = \mathrm{L}_2\mathrm{F}_{\mathrm{threads}} \quad \Rightarrow \quad \mathrm{F}_{\mathrm{threads}} = \frac{\mathrm{L}_1}{\mathrm{L}_2}\mathrm{F}_{\mathrm{down}} = 13.33 \cdot \mathrm{F}_{\mathrm{down}} \qquad \textbf{Eq. 2}$$

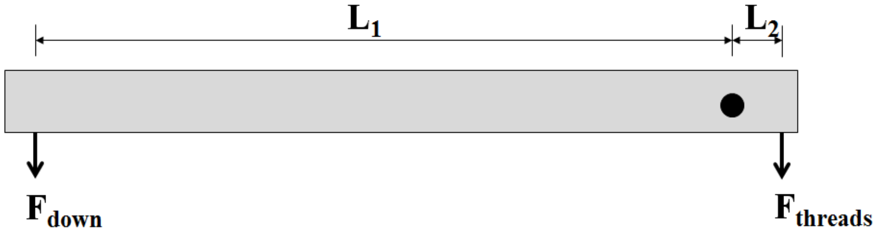

Figure 3. Schematic of lever arm just before thread failure.

Figure 4 shows the average results of the 15-20 thread failure tests for each of the various configurations. This plot was shown in class and students were asked to discuss in small groups what conclusions could be drawn. It is seen that the drill pressed threads were slightly stronger than the hand-drilled threads, perhaps due to the instability of hand drills, resulting in slightly larger holes than the drill press for a given drill bit. Also, despite being twice as thick as the aluminum, the ABS had a much smaller failure force which could have been predicted based on the thread failure force equation (Eq. 1) and knowledge of the material yield strengths.

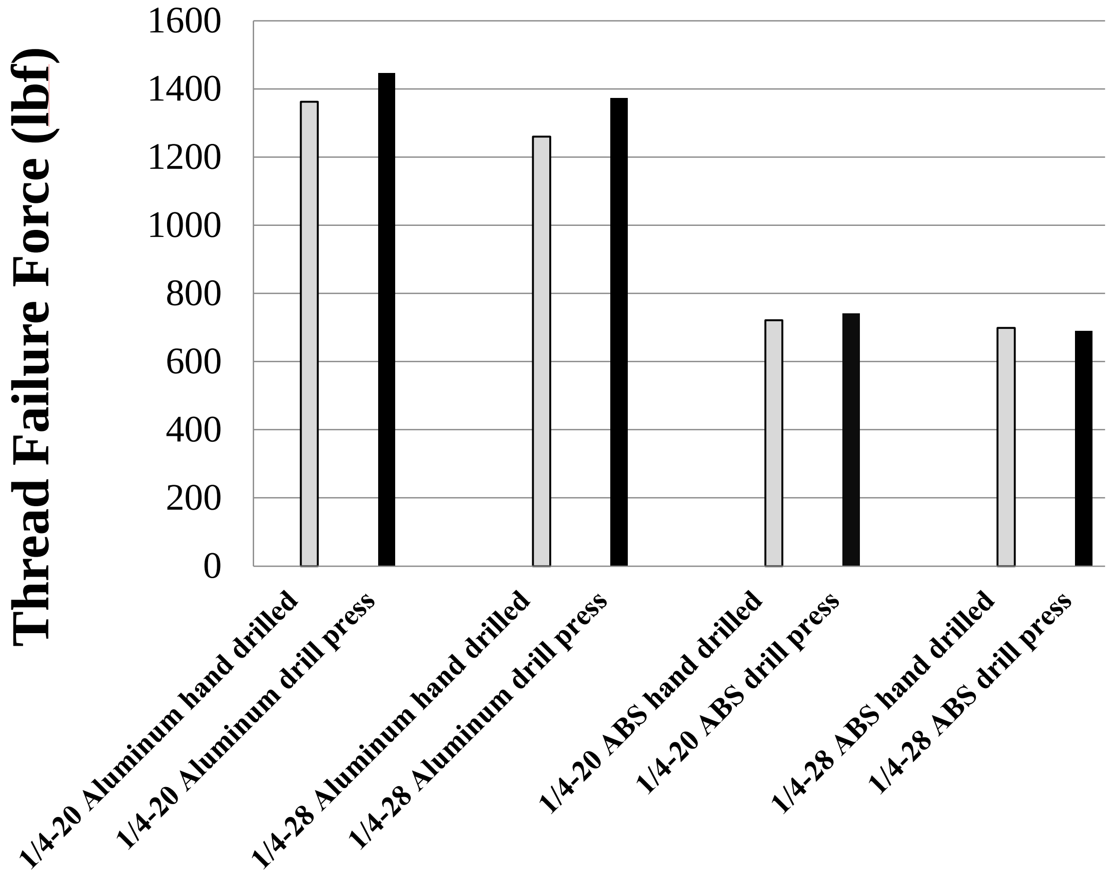

Figure 4. Thread failure results

One may note that thread pitch is not a variable in Eq. 1, which agrees with the similarity between the measured failure forces shown in Fig. 4 (i.e. ¼-28 not stronger than ¼-20). This result is often surprising to the students who think that by having more threads per inch there should be more threads to resist being pulled out thus making them stronger. While there are more threads, each of them is thinner and the overall area of aluminum, or ABS, that needs to deform for the coarse and fine thread to fail is roughly identical. This allows for a brief lesson on the advantages of coarse and fine threads[8].

Yield Strength Comparison

As a final component to the classroom exercise and to check the validity of the thread stripping apparatus data, the yield strength of the ABS and aluminum were determined. One can easily manipulate Eq. 1 to solve for the material yield strength based on a known failure force. The material properties for the ABS and aluminum are also given by the supplier (McMaster Carr), though they are given as a range and with some digging on the website one finds a warning which states that the mechanical properties are not guaranteed. A third method for determining yield strength is to use a hydraulic universal testing machine (Fig. 5a), which mechanical engineering students commonly encounter when taking a deformable mechanics or mechanics of materials course. For this test the aluminum and ABS were machined into a dog-bone shape which was then loaded into the machine which stretched the samples using hydraulic-powered grips. By measuring the force applied, the material deformation, and the cross sectional area, an accurate measure of the material yield strength can be determined.

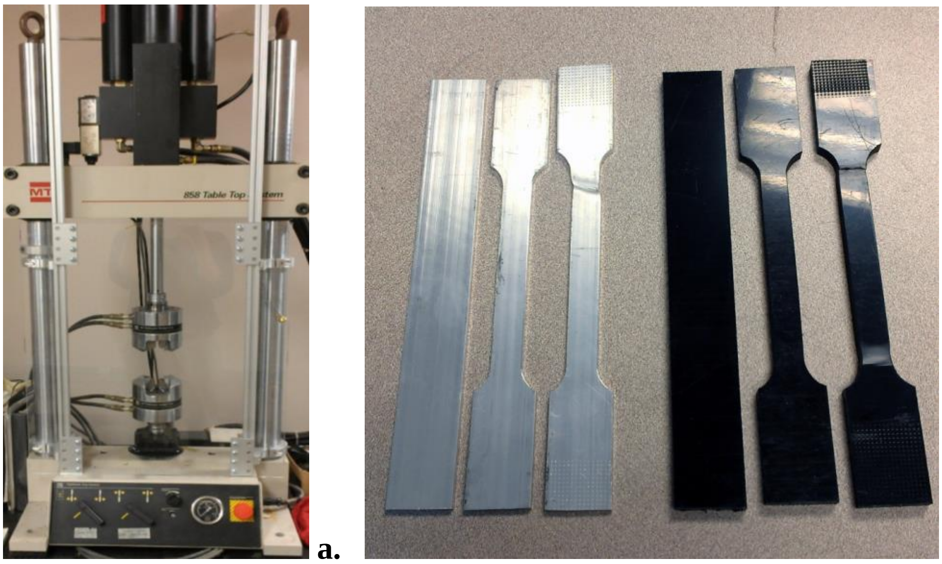

Figure 5. a) MTS 858 test machine; b) original stock, dog-bone sample and tested sample

The instructor did this testing and took video of the procedure to show students in class, though there are YouTube videos[9] that show this as well. The material yield strength results from the three different sources are shown in Table 1. A comparison of the lab apparatus and the MTS tester shows that the ABS results were off 27% while the aluminum results were off by 8% which is considered reasonable based on the simplicity of the lab apparatus. It is believed that the largest source of error lies with the spring scale, particularly at the smaller forces required for stripping the ABS threads. In the future this scale will be calibrated. It is interesting to note that McMaster gave a very conservative estimate for the aluminum yield strength. Overall, the in-class time spent on these additional topics was roughly 20 minutes.

Table 1.

material	**Lab Apparatus** S_y **(psi)**	**McMaster** S_y **(psi)**	**MTS Tester** S_y **(psi)**
aluminum	32,200	16-21,000	29,500
ABS	8000	5100-6100	5800

Project Assessment

To assess how well this drilling, tapping and thread stripping experience impacted student learning a number of measures were used. On the first day of class students were asked how comfortable they were using hand tools. On a scale of 0-10 with 0 meaning zero skill and 10 meaning extremely comfortable the average student judged their comfort with hand tools as 7.1/10. End of course surveys revealed that average student comfort with hand tools was raised to 8.6/10 with 60% of the students reporting an increase and 40% reporting no change. While there was one other project which afforded the opportunity for using hand tools, this exercise was the only formal training with tools and is believed to be the primary motivator for this change in tool comfort. The end of course survey further revealed that 94% of students were confident in their ability to drill and tap a hole on their own. This is a significant increase from the 28% of students who came into the course having any experience with tapping a hole. This result also suggests that the amount of practice afforded during this exercise was adequate for the vast majority of the students.

The final exam for the course included the following problem to test understanding of the thread force calculation:

"An aluminum pressure vessel has an inside diameter of 5 inches and its cover is held on by six Grade 5 Steel 3/8-16 machine screws which are screwed 0.5 inch into threaded holes in the pressure vessel. If the Yield Stress of the aluminum is 30,000 lbf/in^2 and is 81,000 lbf/in^2 for the Grade 5 Steel, how much pressure can the vessel hold before the cover shoots off? Give answer in psi."

A careful review of student work on this problem showed that 85% of the class used Eq. 1 appropriately and used the proper material yield strength in their solution attempt. Considering that each student spent a total of 100 minutes of lab time and 20 minutes of lecture on this subject, these results are considered remarkably successful.

Students were also asked how the exercise could be improved. A fair number of students responded that more time would have been helpful so that they could finish all of their holes. To allow more time for the hands-on portion of the exercise future students will be asked to do the pre-lab reading as per Pappas and Prins[7], which will then be reviewed briefly at the start of lab. Additional time savings may be found by doing the in-lab demonstration for the consolidated lab section instead of two smaller groups, and also by acquiring additional tools.

Additional student suggestions included:

- have one more activity in class which required students to drill and tap at a later time
- show an example of a poorly tapped hole
- include more examples of when/where tapping is used
- spend more time on the vocabulary used with fasteners, drilling and tapping

It is worth noting that a fair number of students also had no suggestions and thought that the exercise was as effective and efficient as possible.

As a concluding thought at the end of this experience the class was asked how difficult they believed it was to learn how to drill and tap a hole. The results ranged from "it was a little tricky" to "it was easier than I imagined." Tools, and the machine shop in particular, can be intimidating to students in that they afford the risk of serious injury and public embarrassment. One desired outcome of the exercise is the students' realization that something which was foreign and seemingly difficult in the shop (i.e. understanding how to drill and tap a hole) is in reality quite simple with a little practice, and henceforth they will be less hesitant to take the initiative in learning other simple shop skills.

Acknowledgements

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Appendix

Thread Stripping Apparatus Materials

- Multipurpose 5000 lbs winch
- Bow spring-scale up to 100 lbs
- 0.25" x 12" x 18" steel plate
- 2" x 3" x 6' rectangular steel tubing
- 1" x 3" x 8” steel bar stock (2)
- 1.25” 5/16-18 grade 7 steel bolts (4)
- bolt, washer, and lock nut in 1/4-20 grade 7 steel (2 each)
- 6' x 0.5" diameter medium grade steel rod stock
- 1" x 1/8" x 3” steel bar stock
- 1/4-20 eyebolts (2)
- 1/4-28 eyebolt
- 1/4” diameter shackle
- 5/16” diameter 240 lbf workload rope (5 ft.)
- mounted pulley
- C-clamps (4)